ERDC/GSL TR-02-13

Geotechnical and Structures Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Innovations for Navigation Projects Research Program

Guide for the Use of Low-Density Concrete in Civil Works Projects

George C. Hoff

August 2002

Innovations for Navigation
Projects Research Program

ERDC/GSL TR-02-13
(TR INP-02-7)
August 2002

Guide for the Use of Low-Density Concrete in Civil Works Projects

by George C. Hoff

Hoff Consulting
250 Saddlewood Drive
Clinton, MS 39056-4070

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under INP Work Unit 33151

Monitored by Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

Contents

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program. The study was conducted under Work Unit (WU) 33151, "Low-Density, High-Strength Concrete for Float-In Construction," managed at the U.S. Army Engineer Research and Development Center (ERDC) Geotechnical and Structures Laboratory (GSL).

Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE; Research Area Manager was Mr. Barry Holliday, HQUSACE; and Program Monitors were Mr. Mike Kidby and Ms. Anjana Chudgar, HQUSACE. Mr. William H. McAnally of the ERDC Coastal and Hydraulics Laboratory was the Lead Technical Director for Navigation Systems; Dr. Stanley C. Woodson, ERDC GSL, was the INP Program Manager.

This report was prepared by Dr. George C. Hoff of Hoff Consulting, Clinton, MS. The work was monitored by Mr. Billy D. Neeley, Principal Investigator of WU 33151, under the supervision of Dr. William P. Grogan, Chief, Concrete and Materials Branch; Dr. Albert J. Bush III, Chief, Engineering Systems and Materials Division; and Dr. David W. Pittman, Acting Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

1 Introduction

1.1 Background and Purpose

This guide provides information for the investigation, selection, and use of materials in the production of low-density concrete for civil works concrete structures. As there are many similarities between normal-density concrete and low-density concrete, the elements discussed in this guide focus only on those areas in which there are differences between the two—in material types, materials processing, mixture proportioning, batching, placing, consolidation, job controls, and other construction-related issues. Emphasis is placed on use of low-density concrete in hydraulic structures. Roller-compacted concrete, shotcrete, rigid pavements, architectural concrete, and concrete for repair are not included.

Information on plans and specifications, coordination between design and field activities, preparation for construction, concrete quality verification and testing, and reporting are similar for both normal- and low-density concrete and are described in Engineer Manual (EM) 1110-2-2000 (Headquarters, Department of the Army (HQDA) 2001) and in Engineer Regulation (ER) 1110-2-1150 (HQDA 1999).

1.2 Engineering Responsibilities and Requirements

The concrete-related engineering responsibilities and requirements during the development of a civil works project that will use low-density concrete are the same as for a project using normal-density concrete. In most instances, both types of concrete will be used on the same project. These responsibilities and requirements are described in paragraph 1-5 of EM 1110-2-2000 (HQDA 2001). Requirements for engineering documents are described in paragraph 8 of ER 1110-2-1150.

1.3 Delays in Contract Awards

If delays of 5 years or longer have occurred between the time of completion of the Engineering Appendix to the Feasibility Report, it will be necessary to reconfirm the validity of the findings of the document relevant to low-density concrete materials prior to the issuance of plans and specifications to the prospective bidders. The availability of the types and sources of cementitious

materials and low-density aggregates should be rechecked. If changes have occurred, it may be necessary to conduct tests to determine the suitability of the currently available materials in combination with the currently available low-density aggregates. All new and relevant information should be provided in the Design Documentation Report (DDR). As the low-density aggregates will most likely come from a commercial source that has been continually producing during the contract delay period, each low-density aggregate source should be checked to ensure future adequate supply. The currently produced aggregates should also be confirmed petrographically to ensure that there have been no significant changes in the source material and the method of aggregate production since the initial investigations. Depending on the results of the petrographic examination, it may be necessary to reevaluate the aggregate source for suitability. The results of such an evaluation should be presented in the DDR.

2 Materials

During the investigations for a civil works structure that incorporates low-density concrete (LDC), it is necessary to assess the availability and suitability of the materials needed to manufacture LDC with qualities meeting the structural and durability requirements of the specific project. Materials involved include cementitious materials, fine aggregate (both normal- and low-density), coarse aggregate (both normal- and low-density), water for mixing and curing, and chemical admixtures. The results of these investigations will be provided in the Engineering Appendix to the Feasibility Report.

This report will not describe in detail all of the materials used to produce LDC but will address those materials that make low-density concrete different from normal-density concrete. The reader is referred to EM 1110-2-2000 for the detailed descriptions of the materials common to both types of concrete and to Holm and Bremner (2000) for a summary of mechanical and physical properties typical in structural low-density and normal-density concretes.

2.1 Low-Density Concrete Classifications

For the purposes of this report, low-density concrete can be classified as structural-grade low-density aggregate concrete; as high-strength, low-density concrete; or as specified-density concrete. All three structural low-density concrete classifications contain aggregates made from pyroprocessed shale, slate, clay, expanded slag, expanded fly ash, and those mined from natural porous volcanic sources. They do not contain low-density insulating aggregates such as vermiculite, perlite, or expanded polystyrene.

2.1.1 Structural-grade low-density aggregate concrete

Structural LDC is defined as concrete that (a) is made with low-density aggregates conforming to American Society for Testing and Materials standard ASTM C 330, (b) has a compressive strength in excess of 17.2 MPa (2,500 psi) at 28 days when tested in accordance with the methods stated in ASTM C 330, and (c) has an air-dry density not exceeding 1,842 kg/m^3 (115 lb/ft^3) as determined by ASTM C 567. Concrete in which a portion of the low-density aggregate is replaced by normal-density aggregate is also considered as structural LDC if it meets criteria (a), (b) and (c) above. The use of normal-density aggregates usually results in some increase in strength and modulus of elasticity. However, these increases are made at the sacrifice of increased weight.

2.1.2 High-strength low-density concrete

High-strength LDC typically achieves strength levels from 34 to 69 MPa (5,000 to 10,000 psi) by incorporating various pozzolans (fly ash, silica fume, metakaolin, calcined clays and shales) combined with normal, mid-range, or high-range water reducers, or both. The water-binder ratio is typically less than 0.45 (by weight), and the air contents are on the low end of the acceptable range. This concrete has an air-dry density not exceeding 2,000 kg/m^3 (125 lb/ft$^{3)}$ as determined by ASTM C 567.

2.1.3 Specified-density concrete

The optimization of concrete density to improve structural efficiency (the strength to density ratio), reduce transportation costs, and also enhance the hydration of high-cementitious concrete mixtures with low water-binder ratios (less than 0.40) is accomplished by replacing part of the normal-density aggregates (coarse aggregate, fine aggregate, or both) with comparable amounts of low-density aggregate. Using this approach, concrete densities from 1,842 to 2,370 kg/m^3 (115 to 148 lb/ft^3) can be produced to meet specific project requirements. These concretes are also sometimes referred to as semi-low-density concrete.

2.2 Cementitious Materials

There are no significant differences between the cementitious materials used for low-density concrete and normal-density concrete. These materials include

a. Portland cement as described in ASTM C 150.

b. Blended hydraulic cements as described in ASTM C 595, provided they contain sufficient amounts of fly ash or natural pozzolan to meet Corps requirements.

c. Pozzolans such as fly ash and natural pozzolan classified and defined in ASTM C 618.

d. Ground granulated blast-furnace slag (GGBF) as described in ASTM C 989.

e. Silica fume as described in ASTM C 1240.

f. Metokaolin, which can be classified as a natural pozzolan and described in ASTM C 618.

Engineer Manual 1110-2-2000 also allows the use of expansive hydraulic cement (ASTM C 845) and air-entraining portland cement (for minor structures, UFGS-03307). While not unsatisfactory, these cements may offer no advantage in low-density aggregate concrete. The benefits of expansive cement most likely will be negated by the lower modulus and porous nature of the low-density aggregates, which can absorb much of the desired expansion of the cement. Air-

entraining cements may not contain sufficient air, as typically required for suitable low-density concretes.

2.2.1 Selection of cementitious materials

The selection of one or several suitable cementitious materials for use in LDC depends on the exposure conditions, the type of structure, the characteristic of the aggregate, the availability of the cementitious material, and the method of construction.

The selection of the cementitious materials for normal-density concrete is influenced by whether the concrete structure is considered mass concrete or structural concrete. Mass concrete (UFGS-03700) is defined as any volume of concrete with dimensions large enough to require measures be taken to cope with generation of heat from the hydration of the cementitious material and attendant volume change to minimize cracking. Low-density concrete typically would not be considered for use as mass concrete because of its reduced weight; however, there have been applications of large mat foundations constructed with LDC to reduce the bearing pressure on underlying soil. When low-density aggregates are used in mass concrete, they tend to aggravate the heat development problem because of their porous structure, which acts as a good insulator. Thus, special provisions must be made for their use.

Cast-in-place structural concrete (UFGS-03301) is defined as concrete that normally will be placed in reinforced concrete elements such as beams, columns, walls, and slabs that have dimensions such that heat generation is not a problem. Typically, precast-prestressed concrete (UFGS-03415) is used in wall panels, roof panels, beams, and girders. These are comparable in shape and dimension to functionally similar members done as cast-in-place concrete. However, for both types of concrete, many features of a structure will fall between the two extremes of being either massive or structural, and the designer will need to decide if measures to limit or mitigate heat generation are needed. In these intermediate-sized structures made with low-density aggregates, peak temperatures may not be a significant problem. However, thermal gradients must be controlled because of the good insulating characteristics of the low-density aggregate, which delay heat dissipation from the concrete.

The factors that affect the amount of heat that is generated (and the peak temperature that the concrete will reach) are the amount and type of the cementitious materials in the concrete, the size of the placement, and the initial placing temperature. The thermal gradients that can lead to cracking are influenced by the peak temperature, the configuration of the structure, and the ambient temperatures at the outside surface of the concrete.

2.2.2 Specification details

The specification details described in EM 1110-2-2000, paragraph 2-2c(2)(b), also apply to low-density concrete.

2.2.3 Other requirements

The investigation of cementitious materials for use in LDC must include an assessment of the impact on cost and availability of special requirements or options. Engineer Manual 1110-2-2000, paragraph 2.2c(3), provides provisions that limit the heat of hydration, provide sulfate resistance, limit the alkali content, and control false set in normal-density concrete. These same provisions also apply to LDC, with the exception of alkali reactivity. Low-density aggregates are generally not reactive. Concretes made with low-density aggregates will not need the use of low-alkali cements, or the use of GGBF slag or pozzolans, unless they are used in conjunction with normal-density aggregates that are reactive. The remaining provisions of EM 1110-2-2000, paragraph 2-2c(3), should be invoked based only on a demonstrated need for the cement having these characteristics.

2.2.4 Pozzolans

Pozzolans are commonly used in LDC. The classes of pozzolans most likely to be available are classes F and C fly ash and silica fume. Class N pozzolans, such as metakaolin, may be considered at those sites where a source of natural pozzolan is available.

The Solid Waste Disposal Act, Section 6002, as amended by the Resources Conservation and Recovery Act of 1976, requires all agencies using Federal funds in construction to allow the use of fly ash in concrete unless such use can be shown to be technically improper. The basis of this regulation is both energy savings and waste disposal, since most fly ash available today is the result of the burning of coal for electrical power.

The use of pozzolan in LDC should be considered coincident with consideration of the types of available cements. Portland cement to be used alone should always be considered in the specifications, as well as blended hydraulic cements or the combination of portland cement with slag cement or pozzolan unless any of these combinations is determined to be technically improper. Blended hydraulic cement meeting the requirements of ASTM C 595 Type I(PM) should not be specified because of the possibility that it could contain less than 15 percent, by mass, of fly ash or natural pozzolan. The fly ash or natural pozzolan component of any blended cement must comprise a minimum of 15 percent, by mass, of the total cementitious materials (EM 1110-2-2000, paragraph 4-3b(7)).

Pozzolans are often used in LDC to compensate for a lack of fines that can occur when low-density aggregates are used (see Chapter 3). The use of Class F fly ash as a partial replacement of portland cement typically results in a reduction of heat of hydration of the cementitious materials at early ages. The use of Class C fly ash in the same proportion usually results in substantially less reduction or perhaps no reduction in heat of hydration. However, some Class F fly ashes have high calcium oxide contents and are more reactive than those with low calcium oxide contents. These Class F fly ashes generally do not provide the magnitude of heat reduction typically expected with the use of a Class F fly ash. One approach to compensate for this is to specify a maximum calcium oxide

content of 8 percent in addition to the standard requirements of ASTM C 618. In fairly thick sections of LDC, the use of Class F fly ash is preferred. Both Class F and Class C fly ash have been found to delay initial and final set of the mixture.

2.2.5 Availability investigation of cementitious materials

The availability investigations of cementitious materials for use in LDC should follow those described in EM 1110-2-2000, paragraph 2-2d, for normal-density concrete.

2.3 Aggregates

One of the most important factors in establishing the quality and economy of LDC is a determination of the quality and quantity of low-density aggregates available to the project. Not all low-density aggregates are of equal quality. The differences between aggregates can be quite significant. In most cases, the low-density aggregates will not be produced close to the project site, thus requiring significant transportation, delivery scheduling, and stockpiling at either the concrete producer's location or the project site.

2.3.1 Particle density

Low-density aggregates have a low particle density because they contain a cellular pore structure. The cellular structure within the aggregate can occur naturally (volcanic sources) or as the result of heating shale, slate, or clay to 1,180 °C (2,160 °F) in a rotary kiln, or can occur in expanded slag or expanded fly ash. In all these heating processes, gases are evolved within the pyroplastic mass, causing expansion and a vesicular structure that is retained as the material cools. The various vesicles are, to varying degrees, not interconnected. The resulting structure causes the particle density of the raw material to change from approximately 2.65 before heating to less than 1.55 after cooling.

2.3.2 Particle shape and surface texture

Depending on the basic material of the low-density aggregate and the method of production, considerable differences in particle shape and texture can occur. Shapes may be rounded, angular, cubical, or irregular. Textures may range from fine-pore, relatively smooth skins to highly irregular surfaces with large exposed pores. The porous surface texture of low-density aggregate causes the boundary or contact zone between the cementitious matrix and coarse aggregate to be almost indistinguishable in mature concretes. The particle shape and surface texture directly influence workability, fine to coarse aggregate ratio, cement content requirements, water demand in concrete mixtures, and the various physical properties of the concrete.

2.3.3 Absorption characteristics

Due to their porous nature, low-density aggregates absorb more water than comparable normal-density aggregates. Based upon 24-hr absorption tests

conducted in accordance with ASTM C 127 and ASTM C 128, structural-grade low-density aggregates typically absorb between 5 percent and greater than 25 percent water by weight of dry aggregate. Normal-density aggregates generally absorb 2 percent or less. Pores close to the surface are readily permeable and fill within the first few hours of exposure to moisture. The interior pores fill very slowly, with many months of submersion needed to become saturated. A small fraction of the interior pores are not interconnected and may never become saturated.

2.3.4 Gradations

Grading requirements for low-density aggregates deviate from those of normal-weight aggregates (ASTM C 33) by requiring a larger mass of the low-density aggregate to pass through to the finer sieve sizes. This modification in grading (ASTM C 330) recognizes the increase in density with decreasing particle size of low-density aggregate. This modification yields the same volumetric distribution of aggregate retained on series of sieves for both low- and normal-density aggregates.

Producers of structural LDC normally stock materials in several standard sizes such as coarse, intermediate, and fine aggregate. The maximum size is typically 19 mm (3/4 in.) By combining size fractions or by replacing some or all of the fractions with normal-density aggregates, a wide range of concrete densities can be obtained. Normal-density aggregates used in conjunction with low-density aggregates should conform to ASTM C 33.

2.3.5 Maximum strength ceiling

Low-density aggregates have a strength ceiling in the same manner as do normal-density aggregates. With continuing increases in compressive (or tensile) strength, a point is reached where no further improvements in strength can be obtained even with increased cementitious content or lower water-binder ratios. At this point, the strength of the low-density coarse aggregate particle, or the transition zone, will determine the limiting strength. Strength ceilings of low-density aggregate produced from differing quarries and plants will vary considerably. The variation is due to the structural characteristics of the pore system developed during the firing process. Some expanded clay aggregates that undergo a pelletizing process have the clay pellets treated with limestone solutions prior to expansion, with a resulting harder exterior surface and a subsequent higher strength ceiling.

2.3.6 Sources of aggregate

Unlike the case for normal-density aggregates, there will no onsite source for low-density aggregates. Only commercial sources exist, and these can be identified by contacting the Expanded Shale, Clay and Slate Institute (ESCSI). For normal-density aggregates used in conjunction with low-density aggregate, both onsite and commercial sources can be considered.

Preliminary investigations to determine potential low-density aggregate sources should be performed during the feasibility phase. Detailed investigations should be performed during the preconstruction engineering and design (PED) prior to issuance of plans and specifications. All sources investigated during the PED should be documented in the Engineering Appendix to the Feasibility Report, and those sources found capable of producing low-density aggregates of suitable quality and also of conditioning those aggregates to desired levels of absorption prior to shipment to the job site should be listed in the contractor's information in the specifications.

Representative sources within reasonable shipping distances of the project should be investigated. These sources may include low-density aggregates made from a variety of different source materials (e.g., slate, shale, clay). The source material is generally not a concern as long as the expanded aggregate meets the requirements needed for the job (e.g., strength, gradation, absorption). The investigation should also include the aggregate producer's capability to supply the needed amounts of aggregate in a timely fashion consistent with the concrete production demands. Many low-density aggregate producers operate at reasonably high levels of production to meet their current client's needs and do not have the ability to expand the plant capacity for on-off projects. The investigation should be comprehensive enough to ensure that more than one source of low-density aggregate with appropriate aggregate sizes is available to the contractor. It is not recommended to use low-density aggregates from different sources concurrently during production because the differences in aggregate strength and absorption between sources will make mixture control very difficult. The investigation should result in a list of low-density aggregate qualities that are required for the project and an acceptance limit for each quality. The aggregate qualities and their respective limits must be documented in the Engineering Appendix to the Feasibility Report and will be used in preparation of specifications for the project.

2.3.7 Availability investigation

The objectives of the availability investigation are to determine the required aggregate quality for the project, as well as the quality of the aggregate available to the project, and to ensure that sufficient quantity of the required quality is available. The requirements outlined in EM 1110-2-2000, paragraph 2-3b, for the availability investigation for normal-density aggregates should be followed when these aggregates are used in conjunction with low-density aggregates. There will be no field exploration and sampling of undeveloped sources for the low-density aggregate unless the aggregate to be used is a naturally occurring low-density aggregate mined from volcanic sources such as pumice and scoria.

2.4 Water for Mixing and Curing

For low-density concrete, both the water used at the aggregate plant for conditioning the aggregate and the most readily available water sources at the project site should be investigated during the PED phase for suitability as mixing water. If multiple potential sources of the low-density aggregate are being

considered, the conditioning water at all sources should be investigated. There always exists a possibility of the water absorbed in the aggregate becoming part of the mixing water and, at later ages, contributing to the continuing hydration of the cement. Therefore, the quality of this water is important. The site water will also be used for curing and must be satisfactory for this application. In addition, the water that is in contact with the structure, both during construction and after the structure is completed, should be tested to determine if it contains a concentration of chemicals that may attack the hardened concrete.

Engineer Manual 1110-2-2000, paragraphs 2-4b and 2-4c, should be consulted for the requirements for mixing and curing water, respectively.

2.5 Chemical Admixtures

The chemical admixtures that may be used for LDC projects are the same as may be used for normal-density concrete projects. These include air-entraining admixtures (ASTM C 260), accelerating admixtures, water-reducing admixtures, retarding admixtures, water-reducing and retarding admixtures, and water-reducing and accelerating admixtures, high-range water-reducing admixtures, and high-range water-reducing and retarding admixtures. All of the latter are discussed in ASTM C 494. Any admixtures may be used in low-density concrete when their use on the project results in improved quality and economy. When admixtures are considered during the PED phase to provide special concrete properties, trial batches with materials representative of those that will be used for the project should be proportioned and tested. The effects of the admixture(s) on the concrete properties and the required dosage rate(s) should be reported in the Engineering Appendix to the Feasibility Report. Admixtures proposed for use during construction should be checked with trial batches by the ERDC Materials Testing Center (MTC) using the actual project materials. However, if the source of the concrete is a ready-mix plant with a recent history (6 months or less) of use of the admixture(s) with project materials, trial batches need not be required. This may not be common, as most ready-mix plants do not routinely produce low-density concrete.

In EM 1110-2-2000, paragraph 2-5 provides detailed descriptions of most chemical admixtures that are used in both normal- and low-density concretes. The range of dosage rates is also indicated. For LDC batching, the admixtures are generally added to the mixture late in the mixing cycle (see Chapter 4). If the low-density aggregate does not contain adequate moisture prior to mixing, some quantity of the mixing water may be absorbed during mixing. Chemical admixtures added to the mixture early in the mixing cycle may then be absorbed into the aggregate, thereby reducing the amount available to perform the desired action.

The Corps policy (stated in paragraph 2-5b(1) of EM 1110-2-2000) that all civil works concrete should be air-entrained using an air-entraining admixture (AEA) should be strictly adhered to for LDC. Air entrainment will improve the workability of the concrete, reduce bleeding and segregation, and, most importantly, improve the frost resistance of the concrete. The AEA should be

added to the concrete mixer separately and not intermixed with other admixtures. The various influences on achieving the desired air content in freshly mixed concrete are described in EM 1110-2-2000 for normal-density concrete, and these also apply to low-density concrete.

There is very little published information on the use of antiwashout admixtures (AWA) with LDC, as these types of concrete typically are not placed underwater. In the event that there is a need to perform underwater placement of LDC on civil works projects, the successful use of AWA in that concrete should be demonstrated in the ERDC MTC.

3 Mixture Proportioning Considerations

This chapter describes a general method for selecting and adjusting mixture proportions for structural low-density concrete. These methods are also applicable to concretes containing a combination of low-density and normal-density aggregate. Modifications to this method can be, and often are, made in the trial mixture development with specific materials for given project requirements.

3.1 Selecting Concrete Mixture Proportions

The manner of selecting mixture proportions for low-density concrete varies throughout the United States. East of the Mississippi River, proportioning is typically done by mass in a manner similar to that for normal-density concrete (ACI 211.1). This is practical only when the low-density aggregates have had sufficient moisture conditioning so that their apparent specific gravity can be determined. Initial trial batches done in this manner typically have unit weights within 30 kg/cu m (a few pounds per cubic foot) of the desired density and can then be adjusted. In other areas of the country the procedures described in ACI 211.2 are followed, and these are described in paragraph 3.6 of this guide.

With proper selection of mixture proportions, economical, durable low-density concretes meeting design requirements can be readily produced. Depending on the types of structures, the LDC mixture proportions may be selected by the ERDC (U.S. Army Engineer Research and Development Center) or by the contractor. Any new materials proposed for use after the initial mixture proportioning studies must be proportioned by ERDC or the contractor's commercial laboratory using actual project materials in a new mixture proportioning study.

3.2 Basis for Selection of Proportions

The process of selecting a low-density concrete mixture proportion is similar to that used for normal-density concrete, with added attention given to the influence of the high water-absorption characteristics of the low-density aggregate. The selection process is based on optimizing several desirable characteristics to meet project requirements. The characteristics to be optimized are economy, strength, durability, and placeability. A summary of basic mixture

proportion criteria for structural low-density concrete and normal-density concrete exposed to a marine environment is presented as Table 3.1.

3.2.1 Economy

The primary reason for systematically determining mixture proportions is economy. Low-density aggregates typically cost more than normal-density aggregates because of the energy costs associated with their production, so it is even more important to optimize their use. For normal-density concrete, the maximum economy is achieved by minimizing the amount of cement used, and where appropriate, by replacing portland cement with usually less expensive pozzolan or GGBF slag. For LDC, the cement contents tend to be slightly higher, by 23 to 47 kg/m^3 (40 to 80 lb/yd^3) for comparable strength levels. The use of pozzolan such as fly ash or GGBF slag is extremely useful with low-density aggregates, as it supplies finer particles typically not found in low-density aggregate gradations and helps reduce the heats of hydration, thus negating some of the heat retention in the LDC that results because of the insulating characteristics of the aggregate. In normal-density concrete, the economy is also improved by using the largest nominal maximum size aggregate (NMSA) consistent with the dimensional requirements of the structure on the project. With low-density aggregates, it is unusual to find NMSA larger than 19-mm (3/4 in.). Even smaller NMSA (12.5-mm (1/2 in.) or 9.5-mm (3/8 in.)) are more prevalent with some low-density aggregate producers.

3.2.2 Strength

Strength is an important characteristic of LDC, but other characteristics such as durability, permeability, and wear resistance may be equally or more important. Their relationship to strength is not as well defined as for normal-density concrete because of the variability among all the low-density aggregates that exist. Descriptions of the strength mechanisms and relationships for low-density concrete are presented in Holm and Bremner (2000). Since the materials that comprise LDC are complex and variable, accurate predictions of strength cannot be based solely on relationships to other parameters such as w/c or w/(cm), but should be confirmed by tests of cylinders made from trial batches with the materials used on the project. Normal-density structural concrete typically uses the strength at 28-days age as a parameter for design, concrete proportioning, and evaluation of concrete. The typical use of pozzolan or GGBF slag in LDC tends to delay the early strength gain of the concrete, and later ages may be more appropriate for design purposes. Where there are strength requirements for form removal and form anchorage, the LDC may need to be proportioned for adequate early strength. Normal-density concrete typically uses a minimum compressive strength of 3.5 MPa (500 psi) for form removal and form anchorage, and the same minimum should also be used with LDC. Low-density aggregates also have strength ceilings, as described in Chapter 2, and those should be taken into consideration in proportioning for strength. The absorbed water in the low-density aggregate contributes to continual hydration of the cementitious material in the concrete for prolonged periods of time, thus continually improving strength and reducing volume changes in the concrete.

3.2.3 Durability

Low-density concrete must resist deterioration by the environment to which it is exposed, including freezing and thawing, wetting and drying, chemical attack, and abrasion. Low-density aggregates are generally considered to be frost resistant because of their porous structure that is never completely filled with moisture and their relatively inert solids as a result of the thermal processes used to form them. The concrete containing these aggregates must still have a proper air-void system, which is achieved by using an air-entraining admixture. All exposed LDC placed should be air entrained unless it is shown to be improper for a specific situation. The LDC should also have reached an appropriate maturity before being exposed to an initial freezing action and subsequent continual cycles of freezing and thawing. For an initial freezing action, the concrete should have a compressive strength in excess of 3.5 MPa (500 psi), with compressive strengths being approximately 24 MPa (3,500 psi) before cycles of freezing and thawing begin. The abrasion resistance of LDC is comparable to that of normal-density concrete, although the mechanism by which the concrete surface is removed is different for the two types of concrete (see Hoff 1989). Generally, the durability is also improved by the use of low w/c or w/(cm), since that reduces permeability and the penetration of aggressive liquids.

3.2.4 Placeability

Placeability, including satisfactory finishing characteristics, encompasses traits described by the terms "workability" and "consistency." Engineer Manual 1110-2-2000 describes workability as that property of freshly mixed concrete that determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. It further describes consistency as the relative mobility or ability of freshly mixed concrete to flow. Both terms are applicable to both normal- and low-density concrete. Workability embodies such concepts as moldability, cohesiveness, and compactability. It is affected by the low-density aggregate grading in conjunction with any normal-density aggregate that may also be used, the particle shape of the aggregate (angular, cubical, rounded, irregular), proportions of aggregates (both types), the quantities and qualities of cementitious materials used, the presence or absence of air-entrainment and chemical admixtures, and the consistency of the mixture. The slump test, ASTM C 143, is widely used to indicate the consistency of LDC mixtures used in normal construction. Other consistency tests such as the Vebe, drop table, compacting factor, and Kelly ball are also available; however, typically, these are used on stiff mixtures and seldom on low-density mixtures. Moldability, cohesiveness, compactability, and finishability are evaluated primarily by visual observation and, therefore, the evaluations are somewhat subjective.

Since most contractor and Corps personnel have had little exposure to the use of LDC in civil works projects, it is recommended that specialists in low-density concrete production and placement be retained in the early stages of construction to assist both the Corps and the contractor in initiating the project smoothly. The Corps policy for normal-density concrete is that no additional water should be added to the mixture after the concrete is batched. However, it is often necessary, and entirely permissible, to add water to a LDC mixture on the job to replace free

water that has been absorbed by the low-density aggregate in order to bring the concrete up to the desired slump. This water does not add additional free water to the concrete because some of the free water had become absorbed water; also, this water brings the free water content back to levels that are needed to produce the specified slump. Preconditioning the aggregate by soaking in shallow water or thorough sprinkling for several days will saturate the LDA to a sufficient degree that water intake into the LDA particles will be minimized during mixing and transport.

3.3 Low-Density Aggregates

Compared to normal-density concrete, the principal factors necessitating modification of proportioning and control procedures for LDC are the greater absorptions and the higher rates of absorption of most low-density aggregates.

3.3.1 Absorption and moisture content

Low-density aggregates containing some moisture are preferable to dry aggregates at the time of mixing, as they tend to absorb less water during mixing and therefore reduce the possibility of loss of slump as the concrete is being mixed, transported, and placed. Low-density aggregates having some amount of moisture preconditioning have fewer tendencies to segregate in storage. The water that is contained in the aggregate is accounted for in the mixture-proportioning procedure.

Ideally, it is desirable to precondition the low-density prior to its use by adding sufficient moisture to it at the aggregate production plant, and then maintaining or increasing that level of saturation at the concrete production plant (see paragraph 5.2.5). This is often not done, but should be required in the project specifications in very specific language. When concrete is made with low-density aggregates that have not been thoroughly preconditioned, and have low initial moisture contents (usually less than 8 to 10 percent) and relatively high rates of absorption, it may be desirable to mix the aggregates with one-half to two-thirds of the mixing water for a short period of time prior to the addition of the cementitious materials and any chemical admixtures. If the chemical admixtures are absorbed by the aggregates, they are not available to perform their job in the matrix. The supplier of the low-density aggregate should be consulted about the need for moisture preconditioning and mixing.

It should be noted that there are special considerations to be followed when using preconditioned aggregates during the winter season to avoid ice lumps in aggregate stockpiles and the prevention of early freezing of the LDC. Most moisture preconditioning methods will not fill all the available pore space in the aggregates, and the freezing of the absorbed moisture in the aggregate typically does not cause an expansion of the aggregate and subsequent disruption of the concrete. The guidelines in ACI 306R for cold weather concrete also apply to LDC. Stockpiles of presaturated low-density aggregates must be heated during the cold weather construction season.

When producing trial batches in the laboratory using the specific gravity method per ACI 211.2, the specific gravity of the low-density aggregate should be determined at the moisture content anticipated prior to use (see paragraph 3.4 of this guide).

3.3.2 Gradation

Low-density aggregates and normal-density aggregates used to produce LDC should be graded within limits of generally accepted specifications, such as ASTM C 330 and C 33, respectively. A well-graded aggregate will have a continuous distribution of particle sizes, which produce a minimum void content in the concrete and thus require a minimum amount of cementitious material to fill the voids. This will result in the most economical use of the cementitious material, produce maximum strength, and minimize volume change due to drying shrinkage.

In general, the largest total volume of aggregate in concrete is achieved when (a) the coarse aggregate is well graded from the largest to the smallest sizes, (b) the particle is rounded to cubical in shape, and (c) the surface texture is least porous. Many low-density aggregates will not meet any of these considerations, with an end result that smaller amounts of coarse aggregates are used, thus increasing the amount of fine aggregate used. The same factors of grading, particle shape, and texture also affect the percentage of fine aggregate required, with a minimum percentage of fine aggregate being associated with a rounded or cubical shape and a smooth texture. When well-graded normal-density sand is used to replace low-density fine aggregate, the proportion of coarse low-density aggregate is typically increased. The proportion of coarse aggregate should approach the maximum consistent with workability and placeability, unless tests show that a lesser proportion provides optimum characteristics.

With LDC, the strength may often be increased by reducing the NMSA without increasing the cementitious material content. This reduction may also increase the density of the concrete. Low-density coarse aggregates typically have maximum sizes of 19-mm or 12.5-mm (3/4 or 1/2 in.). Some suppliers may produce only to that one size, while others produce to both sizes. Maximum aggregate sizes larger than 19 mm (3/4 in.) are not common.

3.3.3 Fineness modulus

The fineness modulus of low-density fine aggregate requires some additional understanding and is described in ACI 211.2.

For normal-density aggregate, the bulk specific densities of fractions retained on the different sieves are nearly equal. Therefore, percentages retained on each size indicated by weight also give a true indication of percentages by volume. This is not true for low-density aggregates. The bulk specific density of the various fractions of low-density aggregate increases as the particle size decreases. Some coarse aggregate particles may float in water, whereas material passing the No. 100 sieve may have a specific density approaching that of normal-density fine aggregate. It is the volume occupied by each size fraction, and not the weight

of the material retained on each sieve, that determines the void content and paste content required to provide workability of the concrete. For comparison purposes, the percentages retained on each sieve and the fineness modulus by weight and volume are calculated for a typical aggregate and shown in Table 3.1.

In this example, the fineness modulus by weight is 3.03, whereas it is 3.23 by volume. The fineness modulus of 3.23 by volume indicates a coarser grading than that normally associated with a fineness modulus of 3.03 by weight. Therefore, the low-density aggregate tends to require a larger percentage of material retained on the finer sieve sizes, on a weight basis, than does normal-density aggregate to provide an equal size distribution by volume.

Since it is impractical to calculate the fineness modulus of low-density fines on a volume basis, ACI 304.2R, paragraph 4.3.4, suggests that it be calculated on a weight basis similar to normal-density fine aggregate. The fineness modulus, calculated on weight basis, should then be reduced by 0.20.

Table 3.1
Comparison of Fineness Modulus by Weight and Volume for Typical Low-Density Aggregate[1]

Sieve Size No.	Opening, mm (in.)	Percent Retained, Weight	Cumulative Percent Retained, Weight	Bulk Specific Density, SSD Basis[2]	Percent Retained, Volume	Cumulative Percent Retained, Volume
4	4.75 (0.187)	0	0	--	0	0
8	4.00 (0.0937)	22	22	1.55	26	26
16	1.18 (0.0469)	24	46	1.78	25	51
30	600μ (0.0234)	19	65	1.90	19	70
50	300μ (0.0117)	14	79	2.01	13	83
100	150μ (0.0059)	12	91	2.16	10	93
Pan		9	100	2.40	7	100

[1]From ACI 211.2.
[2]SSD = saturated-surface dry condition.

3.4 Water-Cement/Water-Cementitious Ratio

The cementitious material used to make LDC is typically portland cement or a combination of portland cement and supplementary materials, as described in Chapter 2. When only cement is used as the cementitious material, the ratio (by weight) of water divided by cement is called the water-cement ratio and is typically expressed as "w/c." When cement and some supplementary cementing material are used together as the cementitious material, the weight of water divided by the total amount of cementitious material is called the water-cementitious ratio (or the water-binder ratio); this is typically expressed as

w/(c+m), w/(cm), w/b, w/(c+s), or w/(c+p). The Corps of Engineers typically uses w/(c+m).

Low-density concrete can be proportioned on the basis of an approximate water-cement or water-cementitious ratio when the absorption of the low-density aggregate has been determined. This method is based on the fact that the sum of the weights of all the ingredients in the mixture is equal to the total weight of the same mixture. Based on knowing the unit weight of a LDC containing a particular aggregate, or estimating it from the specific gravity factor of the aggregate, the weight of the low-density aggregates in the unit volume of the concrete can be estimated.

When trial mixtures are proportioned by procedures other than the weight method, the net w/c or w/(c+m) cannot be established with sufficient accuracy to serve as a basis for mixture proportioning. In these trial mixtures, the proportioning is based on a cement (or cementitious material) and air content basis at the required consistency (see paragraph 3.6). For the control typically required on Corps projects, this is may not be a suitable approach.

3.5 Air Entrainment

Air-entrainment should be used in most LDCs. It enhances workability, improves resistance to freeze-thaw cycles and deicer chemicals, decreases bleeding, and tends to obscure minor grading deficiencies. When severe exposure is not anticipated, the use of air entrainment may be waived, but the beneficial effects on concrete workability and cohesiveness should not be underestimated. In general, the air contents should not be less than 4 percent. The entrained air also lowers the unit weight of the concrete, and that may be helpful.

The amount of entrained air recommended by ACI 211.2 for low-density concrete that may be subjected to freezing and thawing or to deicer salts is 4 to 6 percent when the NMSA is 19 mm (3/4 in.) and 4.5 to 7.5 percent when the NMSA is 9.5 mm (3/8 in.). Use of some supplementary cementing materials may tend to reduce air content for given amounts of AEAs, but these losses can be determined and adjusted for in the trial batches.

It should be noted that the addition of air to LDC decreases the strength of the concrete in the same manner as do air additions to normal-density concrete. However, the reductions tend to be smaller if slumps are 5 in. or less and the cement contents are as recommended.

The volumetric method of measuring air (ASTM C 173) is the most reliable method of measuring air content in LDC and is recommended for both laboratory and field use. This method does require more time than does a pressure method, and may require an adjustment in the frequency of field acceptance tests for large, continuous placements. Use of the pressure method of measuring air (ASTM C 231) is not suitable for use in LDC. The pressure method measures the sum of the air voids both in the paste and the aggregate particles. The amount of air determined to be in the aggregate can easily and reliably be measured in

NDC. This value, called the aggregate correction factor, is subtracted from the percent air indicated by the gage on a pressure meter. However, while the aggregate correction factor is generally small (0.2 to 0.8 percent) and relatively constant for a given NDA, such is not the case with LDAs. Their high and varying porosity makes it difficult to determine a reliable aggregate correction factor. Therefore, the pressure method should not be used to measure air content in LDC.

3.6 Estimating First Trial Mixture Proportions

The best approach to making a first trial mixture of LDC, which has specific properties and uses a particular aggregate from a low-density aggregate source, is to use proportions previously established for a similar concrete using aggregates from the same low-density aggregate source. Such proportions may be obtained from the aggregate supplier or previous Corps projects, and may be the result of either laboratory mixtures or actual mixtures supplied to jobs. These mixtures can then be adjusted as necessary to change the properties or proportions, using the methods (see paragraph 3.7 of this guide).

The following paragraphs, derived from ACI 211.2, provide guidance for proportioning a first trial mixture where such prior information is unavailable. Trial mixtures of LDC can be proportioned by two methods: (1) the weight method, which is typically used for mixtures containing low-density coarse aggregate and normal-density fine aggregate, but can also be applied to specified-density concretes where a portion of the coarse aggregate is normal-density aggregate, and (2) the volumetric method, which can be used for all low-density aggregate concrete and combinations of low- and normal-density aggregates.

ACI 211.2 notes that, of the two methods, the volumetric method is preferred. However, this method cannot give reasonable accuracy to the w/c or w/(c+m) and, therefore, is probably not suitable for Corps projects. Information on both methods is presented below.

3.6.1 Method 1–weight method (specific gravity pycnometer)

This procedure is applicable to low-density coarse aggregate and normal-density fine aggregate mixtures. It can also be applied to specified density concretes where a portion of the coarse aggregate is normal-density aggregate.

Estimating the required batch weights for LDC involves determining the specific gravity factor of the low-density aggregate. This is done using a pycnometer in a method described in Appendix A of ACI 211.2. From the specific gravity factor, the first estimate of the weight of fresh LDC can be made. Additionally, the absorption of low-density coarse aggregate can be measured by the method described in ASTM C 127, or by the spin-dry procedure described in Appendix B of ACI 211.2, which permits the calculation of effective mixing water.

The proportioning follows a sequence of straightforward steps that, in effect, fit the characteristics of the available materials into a mixture suitable for the work. The question of suitability is usually defined in the specifications for Corps jobs and may include some or all of the following:

a. Minimum cement or cementitious materials content.

b. Air content.

c. Slump.

d. Nominal maximum size of aggregate.

e. Strength.

f. Unit weight.

g. Type of placement (pump, bucket, belt conveyor, etc.).

h. Other requirements (strength overdesign, admixtures, and special types of cement and aggregates).

Regardless of whether the concrete characteristics are prescribed by the specifications or are left to the individual selecting the proportions, establishment of batch weights per unit volume of concrete can best be accomplished in the following sequence:

Step 1–choice of slump. If slump is not specified, a value approximate for the work can be selected from Table 3.2. The slump ranges shown apply when vibration is used to consolidate the concrete. Mixtures of the stiffest consistency that can be placed efficiently should be used.

Table 3.2
Recommended Slumps for Various Types of Construction

	Slump, mm (in.)[1]	
Type of Construction	Maximum[2]	Minimum
Beams and reinforced walls	100 (4)	25 (1)
Building columns	100 (4)	25 (1)
Floor slabs	75 (3)	25 (1)

[1]Slump may be increased when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower w/c or w/(cm) and does not exhibit segregation potential or excessive bleeding.
[2]May be increased 25 mm (1 in.) for methods of consolidation other than vibration.

Step 2–choice of nominal maximum size of low-density aggregate. Generally, the NMSA should be the largest that is economically available and consistent with the dimensions of the structure. As noted previously, a 19-mm (3/4-in.) NMSA is what is typically available from low-density aggregate producers. When higher strength concretes are desired, better results can be obtained with reduced NMSA at a given w/c or w/(cm). In no case should the

nominal maximum size exceed one fifth of the narrowest dimension between sides of the forms, one third the depth of slabs, nor three quarters of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands or post-tensioning ducts. These limitations may be waived by the Resident or Project Engineer if workability and methods of consolidation are such that honeycombing and voids can be avoided.

Step 3–estimation of mixing water and air content. The quantity of water per unit volume of concrete required to produce a given slump is dependent on the NMSA, particle shape, and grading of the aggregates, amount of entrained air, and use of chemical admixtures. This quantity is not greatly affected by the quantity of cement or cementitious material. Table 3.3 provides estimates of required mixing water for concretes made with various NMSA, with and without air entrainment. Depending on aggregate texture and shape, mixing water may be somewhat above or below the tabulated values, but the values in Table 3.3 are sufficient for a first estimate. Such differences in water demand are not necessarily reflected in strength, since other compensating factors may be involved.

Table 3.3 also indicates the ACI 211.2-recommended levels of purposely entrained air for durability, workability, and reduction in weight, as well as the approximate amounts of entrapped air in non-air-entrained concrete.

The quantities of mixing water given for air-entrained concrete given in Table 3.3 are typical total content requirements as shown for "moderate exposure." These quantities of mixing water are for use in computing cement or cementitious content for trial batches at 20 to 25 °C (68 to 77 °F). They are maximum values for reasonably well shaped angular aggregates graded within limits of the accepted specifications. The use of water-reducing chemical admixtures (ASTM C 494) may also reduce the mixing water by 5 percent or more. The volume of the liquid admixtures is included as a part of the total mixing water.

Step 4–selection of approximate w/c or w/(cm). The required w/c or w/(cm) is determined not only by strength requirements but also by such factors as durability and finishing properties. For any planned project, it is highly desirable to develop a relationship between strength and w/c or w/(cm) for the actual materials to be used, as other materials may give different results. In the absence of such data, approximate and relatively conservative values for concrete containing ASTM C 150 Type I portland cement can be found in Table 3.4. It should be noted that the average strength selected must exceed the specified strength by a sufficient margin (ACI 214) to keep the number of low tests within specified limits. For severe exposure conditions, the w/c or w/(cm) should be kept low even though strength requirements may be met by a higher w/c or w/(cm). Table 3.5 gives some limiting values for w/c or w/(cm).

Table 3.3 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates			
Slump, mm (in.)	Water/Concrete (kg/m³, lb/yd³) for Indicated Nominal Maximum Size of Aggregate		
	9.5 mm (3/8 in.)	12.5 mm (1/2 in.)	19.0 mm (3/4 in.)
Air-entrained concrete			
25 to 50 (1 to 2)	181 (305)	175 (295)	166 (280)
75 to 100 (3 to 4)	202 (340)	193 (325)	181 (305)
125 to 150 (5 to 6)	211 (355)	199 (335)	187 (315)
Recommended average[1] total air content, percent, for level of exposure			
Mild exposure	4.5	4.0	4.0
Moderate exposure	6.0	5.5	5.0
Extreme exposure[2]	7.5	7.0	6.0
Non-air-entrained concrete			
25 to 50 (1 to 2)	208 (350)	208 (350)	187 (315)
75 to 100 (3 to 4)	228 (385)	216 (365)	202 (340)
125 to 150 (5 to 6)	327 (400)	222 (375)	208 (350)
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2

[1]Additional recommendations for air content and necessary tolerances on air content for control in the field are given in a number of ACI documents (including ACI 201, 345, 318, 301, and 302). ASTM C 94 for ready-mixed concrete also gives air content limits. The various requirements in other documents may not always agree exactly; therefore, during proportioning, consideration must be given to selecting an air content that will meet the needs of the job and also the applicable specifications.
[2]These values are based on the criteria that 9 percent air is needed in the mortar phase of the concrete. If the mortar volume is substantially different from that calculated using the procedures used in this report, the desired air content should be calculated based on 9 percent of the actual mortar phase value.

Step 5–calculation of cement content. The amount of cement per unit volume of concrete is fixed by the determinations made in Steps 3 and 4. The required cement is equal to the estimated mixing water (Step 3) divided by the w/c (Step 4). However, if the project specification includes a separate minimum for cement, in addition to requirements for strength and durability, the mixture must be based on whichever criterion leads to the larger amount of cement. The use of other cementitious materials or chemical admixtures, or both, will affect properties of both the fresh and hardened concrete and should be considered in arriving at a total cementitious content.

Table 3.4
Relationship Between Water-Cement Ratio and Compressive Strength of Concrete

Compressive Strength at 28-Days Age, MPa (psi)	Approximate Water-Cement Ratio, by Weight	
	Non-Air-Entrained Concrete	Air-Entrained Concrete
41 (6,000)	0.41	--
34 (5,000)	0.48	0.40
28 (4,000)	0.57	0.48
21 (3,000)	0.68	0.59
14 (2,000)	0.82	0.74

NOTES:

Values are estimated average strengths for concrete containing not more than 2 percent air for non-air-entrained concrete and 6 percent total air content for air-entrained concrete. For a constant w/c or w/(cm), the strength is reduced as the air content is increased. The 28-day strength values may be conservative and may change when various cementitious materials are used. The rate at which the 28-day strength is developed may also change.

Strength is based on 150- by 300-mm (6- by 12-in.) cylinders moist cured for 28 days in accordance with the ASTM C 31 (sections "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control." These are cylinders cured moist at 23 + 2 °C (73 + 3 °F) prior to testing. The relationship in this table assumes a NMSA of about 19 to 25 mm (3/4 to 1 in.). For a given source of aggregate, strength produced at a given w/c or w/(cm) will increase as NMSA decreases.

Table 3.5
Maximum Permissible Water-Cement Ratios for Concrete in Severe Exposures[1]

Types of Structure	Structure Continuously or Frequently Wet and Exposed to Freezing and Thawing[2]	Structure Exposed to Sea Water or Sulfates[3]
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1-in. cover over steel	0.40	0.35
All other structures	0.45	0.40

[1]Modified from ACI 201.2R.

[2]Concrete should also be air entrained.

[3]If sulfate-resisting cement (Type II or Type V of ASTM C 150) is used, permissible w/c or w/(cm) may be increased by 0.05.

Step 6–estimation of low-density coarse aggregate content. Aggregates of essentially the same nominal maximum size and grading will produce concrete of satisfactory workability when a given volume of coarse aggregate, on a dry, loose basis, is used per unit volume of concrete. Appropriate values for this aggregate volume are given in Table 3.6. For equal workability, the volume of coarse aggregate in a unit volume of concrete depends only on the NMSA and the fineness modulus of the normal-density fine aggregate. Differences in the amount of mortar required for workability with different aggregates, due to differences in particle shape and grading, are automatically compensated for by differences in dry loose unit weight.

Table 3.6
Volume of Coarse Aggregate per Unit Volume of Concrete

NMSA, mm (in.)	Volume (m^3) of Oven-Dry Loose Coarse Aggregates[1] per Unit Volume of Concrete for Different Fineness Moduli of Sand			
	2.40	2.60	2.80	3.00
9.5 (3/8)	0.58	0.56	0.54	0.52
12.5 (1/2)	0.67	0.65	0.63	0.61
19.0 (3/4)	0.74	0.72	0.70	0.68

[1]Volumes are based on aggregates in oven-dry loose condition as described in ASTM C 29. These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced concrete construction. For more workable concrete, such as may be required for pump placement, volumes may be reduced up to 10 percent.

The volume of aggregate in cubic meters, on an oven-dry loose basis, for a unit volume of concrete is equal to the value in Table 3.6. (For a cubic yard, multiply the value in Table 3.6 by 27.) This volume is converted to dry weight of coarse aggregate required in a unit volume by multiplying it by the oven-dry loose unit weight of the low-density coarse aggregate.

Step 7–estimation of fine aggregate content. At the completion of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference.

If the weight of the concrete per unit volume is estimated from experience, the required weight of the fine aggregate is the difference between the weight of fresh concrete and the total weight of the other ingredients. Often, the unit weight of concrete is known with reasonable accuracy from previous experience with the materials. In the absence of such information, Table 3.7 can be used to make a first estimate based on the specific gravity factor of the low-density aggregate and the air content of the concrete. Even if the estimate of concrete weight per cubic meter (cubic yard) is approximate, mixture proportions will be sufficiently accurate to permit easy adjustments on the basis of trial batches.

The aggregate quantities to be weighed out for the concrete must allow for moisture in the aggregates. Generally, the aggregates will be moist, and their dry weights should be increased by the percentage of water they contain, both absorbed and surface. The mixing water added to the batch must be reduced by an amount equal to the free moisture contributed by the aggregate (i.e., total moisture minus absorption).

Sample computations. ACI 211.2 contains a sample problem that follows the seven steps listed above and should be consulted before this approach is used for proportioning.

3.6.2 Method 2–volumetric method (damp, loose volume)

This method can be used for mixtures that are all-low-density (both coarse and fine aggregates) or combinations of low-density and normal density aggregates.

Some low-density aggregate producers recommend trial mixture proportions based on damp, loose volumes converted to batch weights. With this procedure, the total volume of aggregates required, measured as the uncombined volumes on a damp, loose basis, will usually be from 4 to 26 percent greater than 1 m^3 of concrete. Of this amount, the loose volume of the fine aggregate may be from 40 to 60 percent of the total loose volume. Both the total loose volume of the aggregate required and the proportions of fine and coarse aggregate are dependent on several variables that relate to both the nature of the aggregates and the properties of the concrete to be produced. Estimating the required batch weights for the LDC involves estimating cement content to produce a required compressive strength level. The cement content-strength relationship tends to be fairly uniform for a given source of low-density aggregate but varies widely between source.

Table 3.7
First Estimate of Weight of Fresh Low-Density Concrete Consisting of Low-Density Coarse Aggregate and Normal-Density Fine Aggregate

	First Estimate of Low-Density Concrete Weight, kg/m³ (lb/yd³) [1]		
	Air-Entrained Concrete		
Specific Gravity Factor	4 Percent	6 Percent	8 Percent
1.00	1,600 (2,690)	1,560 (2,630)	1,520 (2,560)
1.20	1,680 (2,830)	1,640 (2,770)	1,610 (2,710)
1.40	1,770 (2,980)	1,730 (2,910)	1,690 (2,850)
1.60	1,850 (3,120)	1,810 (3,050)	1,770 (2,990)
1.80	1,930 (3,260)	1,900 (3,200)	1,860 (3,130)
2.00	2,020 (3,410)	1,980 (3,340)	1,940 (3,270)

[1] Values for concrete of medium richness (326 kg/m³ (550 lb/yd³)) and medium slump with water requirements based on values for 75- to 100-mm (3- to 4-in.) slump in Table 3.3. If desired, the estimated weight may be refined as follows if necessary information is available:
--For each 5.9-kg/m³ (10-lb/yd³) difference in mixing water from Table 3.3, correct the weight per cubic meter (cu yd) by 8.9 kg (15 lb) in the opposite direction;
--For each 59-kg/m³ (100-lb/yd³) difference in cement content from 326 kg/m³ (550 lb/yd³), correct the weight per cubic meter (yd³) by 8.9 kg (15 lb) in the same direction.

Estimating cement content. It is recommended that the aggregate producer be consulted to obtain a closer approximation of cement content and aggregate proportions to produce concrete with the desired strength and density with that producer's aggregate. When this information is unavailable, a sufficient number of trial mixtures with varying cement contents should be made to achieve a range of compressive strengths that include the compressive strength desired. As a beginning point, the values in Table 3.8 can be used.

Table 3.8 Cement Content Estimates for Initial Trial Batch of Low-Density Concrete		
	Initial Estimate of Cement Content, kg/m³ (lb/yd³)	
Compressive Strength, MPa (psi)	All Low-Density Aggregates	Low-Density Coarse and Normal-Density Fine Aggregate
41 (6,000)	515 (870)	490 (830)
34 (5,000)	455 (770)	435 (730)
28 (4,000)	395 (670)	370 (620)
21 (3,000)	340 (570)	310 (520)

Sample computations. ACI 211.2 contains a sample problem based on damp loose weights and should be consulted before this approach is used for proportioning.

3.7 Adjusting Mixture Proportions

3.7.1 Volume considerations

In proportioning normal-density concrete (ACI 211.1), the volume displaced or absolute volume occupied by each ingredient of the mixture (except entrained air) is calculated as the weight of that ingredient divided by the product of the specific density of that ingredient and the specific density of water (1.0 when dealing in metric units and 62.4 lb/ft^3 when dealing in non-metric units). The total volume of the mixture is the sum of the displaced or absolute volumes of each ingredient plus the volume of entrained and entrapped air determined by direct test. Calculating the absolute volume of cement (based on dry weight of cement in the mixture) and air (as the percentage of the air, determined by test multiplied by the total volume) is done in the same manner for both low- and normal-density concrete mixtures. The volume displaced by normal-density aggregates is calculated on the basis of saturated-surface dry weights of aggregates and the bulk specific densities (SSD basis) as determined by ASTM C 127 and C 128. Volume displaced by water in normal-density concrete mixtures is therefore on the basis of "net" mixture water. Net mixture water is the water added at the mixer plus any surface water on the aggregate or minus any water absorbed by aggregates that are less than saturated.

The effective volume displaced by low-density aggregate in concrete is calculated on the basis of weights of aggregates with a known moisture content as used, and a specific gravity factor that is a function of the moisture content of the aggregate. The specific gravity factor is determined in accordance with Appendix A of ACI 211.2 and is the ratio of the weight of the aggregates, as

introduced into the mixer, to the effective volume displaced by the aggregates The weight of aggregates as introduced into the mixer includes any moisture absorbed in the aggregate and any free water on the aggregates. Effective displaced volume of water in low-density mixtures is then based on the actual water added at the mixer.

3.7.2 Method 1–weight method (specific gravity pycnometer)

Specific gravity factors. Specific gravity factors (ACI 211.2, Appendix A) generally vary with moisture content of the aggregates. For each aggregate type and gradation, it is necessary to determine the specific gravity factors over the full range of moisture conditions likely to be encountered during concrete production. The variation is approximately linear in the lower range of moisture contents, but may vary from linearity at higher moisture contents. The full curve should be established, and extrapolation should be avoided.

Indicated specific gravity factors of coarse aggregates generally increase slightly with time of immersion in the pycnometer because of continued aggregate absorption. The rate of increase becomes smaller with longer immersion periods. The increase with time of immersion is generally the greatest when the aggregate is tested in the dry condition and will become smaller as the moisture condition before immersion increases. Pycnometer specific gravity factors obtained after 10-min immersion of the aggregates should normally be suitable for mixture proportioning and adjustment procedures. Where some slump loss is anticipated in long-haul ready-mixed concrete due to continued absorption of water into the aggregates, additional water is required to offset the resultant loss of yield. The mixture proportions should be determined on the basis of the 10-min specific gravity factor. However, a calculation of the lower effective displaced volumes of aggregates, based on the longer time specific gravity factor, should provide guidance to the anticipated loss of yield to be compensated for by additional water.

Trial batch adjustments. Mixture proportions calculated by the weight method should be checked by trial batches prepared and tested in accordance with ASTM C 192 or by full-sized batches. Only sufficient water should be used to produce the required slump, regardless of the amount assumed in selecting the trial proportions. The concrete should be checked for unit weight and yield (ASTM C 138) and for air content (ASTM C 173). It should also be carefully observed for proper workability, freedom from segregation, and finishing properties. Appropriate adjustments should be made in the proportions for subsequent batches in accordance with the following steps:

- Re-estimate the required mixing water per unit volume of concrete by dividing the net mixing water by the yield of the trial batch. (In non-metric units, multiply the net mixing water content by 27 for a cubic yard, and divide the product by the yield of the trial batch in cubic feet.) If the slump of the trial batch was not correct, increase or decrease the re-estimated amount of water by 6 kg/m^3 (10 lb/yd^3) for each required increase or decrease of 25 mm (1 in.) in slump.

- If the desired air content (for air-entrained concrete) was not achieved, re-estimate the admixture content required for proper air content and decrease or increase the mixing water content stated in Step 3 (paragraph 3.6.1 of this guide) by 3 kg/m^3 (5 lb/yd^3) for each 1 percent by which the air content is to be increased or decreased from that of the previous trial batch.

- Re-estimate the weight per unit volume of the fresh concrete by increasing or decreasing the anticipated percentage in air content of the adjusted batch from the first trial batch.

- Calculate new batch weights starting at Step 5 of the method (paragraph 3.6.1 of this guide), modifying the volume of coarse aggregate from Table 3.6, if necessary, to provide proper workability.

3.7.3 Method 2–volumetric method (damp, loose volume)

Trial batch adjustments to mixtures designed by the damp, loose volume method should be checked by means of trial batches prepared and tested in accordance with ASTM C 192 or by full-sized batches. Only sufficient water should be used to produce the required slump, regardless of the amount assumed in selecting the trial proportions. The concrete should be checked for unit weight and yield (ASTM C 138) and for air content (ASTM C 173). It should also be carefully observed for proper workability, freedom from segregation, and finishing properties. Appropriate adjustments should be made.

3.7.4 Adjustment procedures

Both field and laboratory mixtures may require adjustment from time to time to compensate for some unintentional change in the characteristics of the concrete or to make a planned change in the characteristics. Adjustment may be required, for example, to compensate for a change in moisture content of the aggregates; to proportion a mixture for more or less cement content; to use chemical admixtures; to use other cementitious materials; or to change slump or air content requirements. Those adjustments can be made with considerable confidence based on either a first trial mixture or on previous field or laboratory mixtures with similar aggregates. Small laboratory mixtures of perhaps 0.03 to 0.06 m^3 (1 to 2 ft^3) total volume will require some further adjustments when extrapolated to field mixtures that may be 100 to 300 times larger in volume. It is recommended that tests of fresh unit weight, air content, and slump be made on the initial field mixtures, and any necessary adjustments be made on the field batching quantities.

When it is desirable to change the amount of cement, the volume of air, or the percentage of fine aggregate in a mixture, or when it is desirable to change the slump of the concrete, it is necessary to offset such changes with adjustments in one or more other factors if yield and other characteristics of the concrete are to remain constant. The following bullet items indicate some of the compensating adjustments, show the usual direction of adjustments necessary, and give a rough approximation of the amount of adjustments per cubic meter of concrete. However, note that the numerical values given are approximations that are

intended only for guidance. More accurate values, obtained by observation and experience with particular materials, should be used whenever possible.

Proportion of fine aggregate. An increase in the percentage of fine to total aggregates generally requires an increase in water content. For each percent increase in fine aggregate, increase the water by approximately 1.8 kg/m^3 (3 lb/yd^3). An increase in water content will require an increase in cement content to maintain strength. For each 1.8-kg/m^3 (3-lb/yd^3) increase in water, increase cement by approximately 1 percent. Coarse and fine aggregate weights should be adjusted as necessary to obtain desired proportions of each, and to maintain required total effective displaced volume. The balance of these adjustments will likely result in an increase in unit weight.

Air content. An increase in air content will be accompanied by an increase in slump unless water is reduced to compensate. For each percent increase in air content, water should be decreased by approximately 3 kg/m^3 (5 lb/yd^3). An increase in air content may be accompanied by a decrease in strength unless compensated for by additional cement (see previous discussion, paragraph 3.5). Fine aggregate weight should be adjusted as necessary to maintain required total effective displaced volume. The balance of these adjustments will usually result in a decrease in unit weight.

Slump. An increase in slump may be obtained by increasing water content. For each desired 25-mm (1-in.) increase in slump, water should be increased approximately 6 kg/m^3 (10 lb/yd^3) when initial slump is about 75 mm (3 in.). This amount would be somewhat less when the initial slump is higher. Increase in water content will be accompanied by a decrease in strength unless compensated for by an increase in cement content. For each 6-kg/m^3 (10-lb/yd^3) increase in water, increase the cement content approximately 3 percent. Fine aggregate weight should be adjusted as necessary to maintain required total effective displaced volume. The balance of these adjustments will usually result in a small decrease in unit weight. A water-reducing admixture can also be added to increase slump with little to no effect upon unit weight.

Adjustment for changes in aggregate moisture. A procedure to adjust for changes in the moisture content of aggregates is as follows:

a. Maintain constant the weight of cement and the effective displaced volumes of cement and air.

b. Calculate new weights for both coarse and fine aggregates, using the appropriate value for total moisture content, so that oven-dry weights of both coarse and fine aggregates remain constant.

c. Calculate effective displaced volumes of both coarse and fine aggregates using weights of the aggregates in the appropriate moisture condition or the specific gravity factor corresponding to that moisture condition.

d. Calculate the required effective displaced volume of added water as the difference between the required cubic meters and the total of the

effective displaced volumes of the cement, air, and coarse and fine aggregates.

e. Calculate the required weight of added water of 1,000 kg/m^3 (1,685 lb/yd^3) by the effective displaced volume of added water determined in the previous step.

3.7.5 Controlling proportions in the field

Proportions that have been established for given conditions may require adjustment from time to time to maintain the planned proportions in the field. Knowledge that the proportions are remaining essentially constant, or that they may vary beyond acceptable limits, can be obtained by conducting tests for fresh unit weight (ASTM C 138), air content (ASTM C 173), and slump (ASTM C 143). These tests should be made at the specified uniform frequency (a given number of tests per stated quantity of concrete, per stated time period, per stated section of structure, etc.) and whenever observations indicate that some changes in the ingredients of the concrete or in the physical characteristics of the concrete are occurring. These tests should be made, for example, when moisture contents of the aggregates may have changed appreciably, when the concrete shows changes in slump or workability, or when there is an appreciable change in added water requirements.

A change in fresh unit weight of the concrete, while the batch weights and air content remain fairly constant, shows that the batch is over yielding (with lower unit weight) or under yielding (with higher unit weight). The over-yielding batch will have lower than planned cement content, and the under-yielding batch will have a cement content higher than was planned.

A change in the aggregate specific gravity factor may be the result of either a change in the moisture content of the aggregate or a basic change in aggregate density. If a moisture test indicates moisture changes, the mixture should be adjusted (as described in paragraph 3.7.4 above). While determination of aggregate moisture content in NDA is a quick, simple, and reliable procedure, such determination for LDA is more time consuming, and arguably less reliable. Therefore, it is more difficult to accomplish this task during production of LDC than for NDC. This is another factor that should emphasize the need for thorough conditioning of LDA stockpiles to a uniform moisture content prior to the start of LDC production.

If the basic aggregate density has changed, a determination of new moisture content-specific gravity factor relationships may be needed. Aggregate density changes may be a result of changes in the raw material or its processing or both. A change in slump may indicate a change in (a) air content, (b) moisture content of the aggregate without corresponding change in batching, or (c) aggregate gradation or density. Each of these factors is also indicated by the fresh unit weight test.

Controlling concrete mixtures in the field also requires recognizing possible changes due to variations in ambient temperature, temperature of ingredients,

length of mixing and agitating time, and other causes. Many of these factors are discussed elsewhere in this report.

3.8 Mixture Proportions Comparison

Table 3.9 shows a comparison between representative proportions of a normal-density concrete and a low-density concrete made with low-density coarse aggregate and normal-density fine aggregate.

Table 3.9
Comparison of Mixture Proportions for Comparable-Strength Normal- and Low-Density Concrete Mixtures

	Normal-Density Concrete	Low-Density Concrete
Type I cement, kg/m^3 (lb/yd^3)	307 (517)	335 (564)
19-mm (3/4-in.) coarse aggregate, kg/m^3 (lb/yd^3)	1,098 (1,850)	534 (900)
Fine aggregate, kg/m^3 (lb/yd^3)	756 (1,275)	801 (1350)
Water, kg/m^3 (lb/yd^3)	183 (308)	193 (325)
Air, percent	4	4
Slump, mm (in.)	75-125 (3-5)	50-110 (2-4)
Freshly mixed unit weight, kg/m^3 (lb/ft^3)	2,355 (147)	1,890 (118)
Difference in weight (percent)	--	-20

Both of these mixtures produced similar strengths. The low-density concrete mixture required 28 kg/m^3 (47 lb/yd^3) more cement to compensate for the lower strength of the low-density aggregate. It also used slightly more fine aggregate (45 kg/m^3 (75 lb/yd^3)) to compensate for the lack of finer particles in the low-density aggregate gradation. The reduced weight of the low-density coarse aggregate led to a 20-percent reduction in the concrete density. Note that the slump range was slightly reduced for the low-density concrete to prevent aggregate segregation during placement.

These are the types and approximate differences that can be expected with the production of low-density concrete and are presented to provide a better understanding of the results of the proportioning procedures described in this chapter.

4 Concrete Production

4.1 General Considerations

Measuring and mixing operations for LDC are similar to comparable procedures for normal-density concrete. However, there are some differences, especially in proportioning and batching, which need to be considered. Other batching methods than those described here may be used in various locations and should be reviewed for adequacy if recommended by aggregate suppliers and ready-mixed concrete producers for a particular project. The requirements for batching and mixing equipment, as outlined for normal-density concrete in paragraph 7-4 of EM 1110-2-2000 (HQDA 2001), also apply for LDC.

4.2 Batching

Depending on the project location, sources of materials, and location of haul roads and access roads, the batching plant for the LDC can be located either offsite or onsite. Because the low-density aggregates are typically small in size, commercial concrete plants are commonly used, provided the plants are close enough that the interval between concrete batching and final placement is less than 1.5 hr and that the required placement rate can be maintained. The type of batching and mixing equipment at each commercial plant being considered for the project should be surveyed and summarized in the Engineering Appendix to the Feasibility Report.

4.2.1 Batch-plant and mixer types

The batch-plant and mixer types described in EM 1110-2-2000, paragraphs 3-1c and 3-1d, for normal-density concrete are also satisfactory for LDC. For large volumes of LDC, the batching and mixing of LDC should be done in stationary mixers. Truck mixing of LDC is successfully done but requires more attention because of variations between trucks, variable haul times and distances, and delays in unloading. These factors can result in lack of concrete uniformity caused by the varying absorption characteristics of low-density aggregates. Plant capacities should also follow the requirements of EM 1110-2-2000, paragraph 3-1e.

4.2.2 Measuring and batching

The following batching methods for LDC have been coordinated with the basic principles set forth in both ACI 211.1 and ACI 211.2.

Free water and absorbed water. One of the first considerations in batching LDC mixtures is a proper understanding of the water used in the mixture.

The total water used per unit volume is divided into two components. One component is the water absorbed by the aggregates, while the other is similar to that in normal-density aggregate concrete and is classified as free water. Free water controls the slump and, when mixed with a given quantity of binder, establishes the strength of the paste. The amount of absorbed water varies with different low-density materials, moisture preconditioning, and mixing times. Absorbed moisture does not change the volume of the aggregate or the concrete because it is inside the aggregate. Most importantly, absorbed water does not affect the w/c or w/(cm) or the slump of the concrete.

Absolute volumes. Low-density concrete uses low-density aggregate particles to the extent necessary to achieve the total weight desired in the hardened concrete. The space that the aggregates occupy within the concrete is called their absolute volume. The sum of the absolute volumes of all the ingredients (including air) must equal the required volume of the mixed concrete.

By definition, the absolute volume of a loose granular material is the net volume of the solid material after removing the voids or air spaces between the particles. The absolute volume can be calculated as

$$\textit{Absolute volume in cubic meters} = \frac{\textit{Weight of loose material in kilograms}}{\textit{Specific density of material}}$$

or

$$\textit{Absolute volume in cubic feet} = \frac{\textit{Weight of loose material in pounds}}{\textit{Specific density of material} \times 62.4}$$

Bulk specific density. The methods used to determine the bulk specific density of normal-density aggregates typically are not used with low-density aggregates because of their variable absorption rates and the resulting difficulty of determining their displaced volume in water. The methods described in ACI 211.2, Appendixes A and B, for measuring the specific density factor (dry) and the moisture content give reliable results.

For coarse low-density aggregate, this method consists essentially of immersing a suitably sized sample (1,000 to 1,500 g) for 24 ± 4 hr in water, allowing it to either surface dry in air or spin dry in a centrifuge. The apparent specific density in this saturated surface-dry (SSD) condition is then measured with a pycnometer or by the displacement method described in ASTM C 127. Half of the SSD sample is oven-dried to determine its percent absorption. The

SSD specific density is then reduced by the percentage of absorption to obtain the oven-dry bulk specific density factor (dry). Other methods for determining the bulk specific density of low-density coarse aggregate have been used and may be considered only if they can be shown to satisfy the project requirements.

For low-density fine aggregate, the oven-dry bulk specific density is determined in much the same manner as for the low-density coarse aggregate material. However, it is difficult to visually determine the SSD condition, and the spin-dry procedure or ASTM C 128 may give more satisfactory results. Other methods for determining the bulk specific density of low-density fine aggregate have been used and may be considered only if they can be shown to satisfy the project requirements.

Unit weight variations. The unit weight of low-density aggregate varies depending on the raw materials used and the size of the aggregate (see Table 3.1). Smaller particles usually have higher densities, specific densities, and unit weights than larger particles. Unit weights also vary due to changes in absorption or moisture content. If the low-density aggregates are batched without adjusting for these variations in unit weight, problems of over- or under-yield of the concrete can result. To prevent such problems, various field adjustments are suggested in ACI 211.2. Essentially, these field adjustments consist of changing the batch weights of the low-density aggregates, both coarse and fine, to ensure that the resulting concrete produces the intended volume or yield.

The dry loose unit weight of the low-density aggregate depends on its specific density, on the grading, and on the shape and size of the particles. Angular-shaped crushed aggregates have more voids or unfilled spaces between the aggregate particles than rounded or spherically shaped pieces. Poorly graded aggregate (i.e., all one size) generally has more voids than a uniformly graded material that has enough smaller pieces to fit into the voids between the bigger particles.

Most low-density aggregate producers continually use the same raw material, the same crushing and screening equipment, and the same production methods. This results in a fairly uniform void content for their products. With no major changes to their raw materials, equipment, or methods, the variation in void content will generally result in less than a 1.0-percent change in the yield of the mixture. Different sized materials from the same production facility may have a different but relatively constant void content. Each production facility has its own characteristic void content value for each aggregate being produced, and this information can usually be obtained from the source.

4.2.3 Batching low-density coarse aggregate

To obtain the proper yield of concrete, it is necessary to maintain the same absolute volumes of low-density aggregates in each batch of concrete by adjusting the batch weights to compensate for changes in unit weights of the low-density aggregates. This may be done by frequently conducting standard unit weight tests on the low-density aggregates during batching operations and then adjusting the batch weights to reflect any changes that may occur in these unit

weights. The principal limitation of this procedure, particularly when production rates are high, is that it may be rather time consuming. ACI 304.5R offers an alternate batching system, described below, that was developed as a faster method. Either method produces satisfactory results. The principal difference in the two systems is that the latter method uses a much larger container for measuring the unit weight–the weighing hopper. The ACI method also provides automatic yield measurements for each batch of LDC.

Calibrating the weighing hopper. The system can be set up for virtually any batching facility that uses a hopper or bin for weighing materials. The first operation is to determine the volume of the weighing hopper.

This is done by discharging the low-density aggregate from the overhead bin containing the aggregate into the weighing hopper until the aggregate level reaches the level of the discharge gate. As overhead bins and weigh hoppers may vary in their configuration, suitable but simple modifications may have to be made to them to ensure that the weighing hopper is filled to a prescribed constant level each time.

The weigh hopper is then filled to the prescribed level, and the total weight of the material (either dry or containing absorbed water) can be read from the weight scales. The hopper is then discharged into a dump truck, and the unit weight of three or four samples is determined in a suitable container. The total hopper weight divided by the average unit weight will give the total volume of the material in the weighing hopper in cubic feet. This volume determination should be performed at least three times to ensure valid measurements. New calibrations will be necessary any time the low-density aggregate is changed or the gradation is changed, as those changes may affect the angle of repose of the aggregate in the hopper and, hence, the volume of aggregate. If no major changes occur in the low-density aggregate, one calibration may suffice for several months. An indicator of a possible need for a new calibration is a problem in the density control of the freshly mixed concrete.

ACI 304.5R gives examples on how to prepare batching charts for low-density coarse aggregate. These charts are based on the assumption that the basic full hopper volume remains the same. From these charts, the batch plant operator simply notes the scale weight of the first full hopper and can then immediately determine the weight needed to complete the batch. These charts can be programmed into an automatic, electronically controlled batching facility or can be used in a semi-automatic plant where all of the ingredients except the low-density aggregate are batched electronically.

If batches less than a full truckload are needed, they should be batched in 1-cu yd increments using the unit weight of aggregate determined on the immediately preceding batch multiplied by the loose volume shown on the mixture proportion.

The total weight and the unit weight of the coarse low-density aggregate should be shown on the delivery ticket for each truck, along with the total weights of all ingredients.

4.2.4 Batching low-density fine aggregate

It is not practical to batch low-density fine aggregate by the same method described above for low-density coarse aggregate, because the low-density fine aggregate has volume changes due to variable bulking with different amounts of surface water. The low-density fine aggregates should be batched by weight in much the same manner as natural sand, with allowances made for total moisture content.

Since the moisture in low-density fine aggregate may be partly absorbed water as well as surface or free water, the moisture meters used in batch plant storage bins for natural sand typically have not been satisfactory for low-density fine aggregate. Satisfactory batching results have been obtained by drying a small sample (about 500 g) of the low-density aggregate being used in a suitable container to a constant weight at 100 to 110 °C (212 to 230 °F). The total moisture (absorbed plus surface moisture) is calculated by comparing the moist weight of the sample to its dry weight. Moisture tests should be conducted several times a day because of solar evaporation and draining from the stockpiles, and also when a fresh supply of low-density fine aggregate is introduced.

To adjust for the proper amount of low-density fine aggregate, the oven-dry unit weight of the material being used is determined as indicated above. If this dry unit weight differs from that shown on the laboratory mixture proportions, the dry batch weight is then changed by multiplying the loose volume by the new dry unit weight just determined. This dry batch weight is increased by the moisture content as previously determined to give the actual scale weight to be used.

The absolute volume, or the displaced volume in the concrete, for a given low-density material, will remain the same even though its density changes or its moisture absorption changes.

4.2.5 Adding admixtures

Except for AEA, chemical admixtures are often added last to LDC batches. They are added separately and not combined together before introducing them into the mixer. Early introduction has the risk that some of the admixture will be absorbed into the low-density aggregate, thus losing some of its expected effectiveness.

4.3 Mixing

The principal difference between mixing normal- and low-density concrete is the absorptive nature of the low-density aggregate. Care should be taken to ensure that a high degree of water absorption by the low-density aggregate has taken place prior to batching and mixing (see paragraphs 5.2.2 and 5.2.3). If the aggregates have not been thoroughly preconditioned with respect to moisture content, some quantity of the mixing water may be absorbed during mixing, thus

creating an apparent higher mixing water demand or a rapid slump loss during delivery and placement. Chemical admixtures added to the concrete may also be absorbed by the aggregates, reducing their effectiveness in the mixture. The time rate of absorption as well as the maximum total absorption must be properly integrated into the mixing cycle to control the consistency.

4.3.1 Charging the mixer

The sequence of introducing the ingredients for LDC into a mixer may vary from one plant to another. Once acceptable procedures for both the moisture preconditioning of the aggregate and batching have been established, these must be repeated as closely as possible at all times to ensure uniformity. These procedures should be summarized in the Engineering Appendix to the Feasibility Report for each batch plant that is to be used. Weather conditions such as ambient temperatures, humidity, and rain or snow on stockpiles can significantly influence the concrete production and should be properly addressed in the planning for concrete production.

4.3.2 Plant mixers

Stationary plant mixers for the production of LDC may be located at the ready-mixed concrete production plant or at the building site. For these type mixers, the low-density coarse aggregate should be placed in the mixer first, followed by the fine aggregate, required water, cement, cementitious materials, and any specified admixture. Each chemical admixture should be batched separately and should be batched at the same point in the charging cycle for every batch. If specified-density concrete is being produced, both the normal- and low-density coarse aggregates should be added simultaneously; if this is not possible, the normal-density coarse aggregate should be placed in the mixer first, followed by the low-density coarse aggregate. Low-density fine aggregate, if used, should be added after the coarse aggregate (either or both types).

After all of the ingredients have been placed into the plant mixer, it should be operated at mixing speeds that will produce a complete mixture that will meet the project specifications and the evaluation tests as described in ASTM C 94. Modern-day plants with twin-axle high-shear mixers may have considerably shorter mixing times than traditional drum mixers. There may be occasions when the plant is used for the purpose of partial or shrink mixing. The batching sequence is the same, as the plant still blends the materials together and does some initial mixing with the mixing being completed in a truck mixer. This process is not ideal for LDC because of variations in consistency that can occur due to water absorption of the aggregate during mixing.

4.3.3 Truck mixers

Truck mixing of LDC is practiced in some areas of the United States. However, the practice is usually not suitable for the large volumes of concrete normally needed on civil works projects because the mixing efficiency varies betweens trucks and is harder to control than a stationary batch plant. The charging or loading of a truck mixer follows the same general practice as for

stationary mixers. Because of lower unit weights, larger amounts of LDC than normal-density concrete can be transported in truck mixers without exceeding legal weight or axle load limits. However, the volume of the LDC in the drum should not exceed the rated capacity of the drum or 63 percent of the drum volume when used as a mixer, nor 80 percent of the drum volume when used as an agitator in accordance with ASTM C 94.

4.4 Mixer Operation

4.4.1 Transportation and waiting time

Depending on the location of the batch plant(s), there will be differences in the transportation times for the concrete, and there always is the possibility of delays in unloading. This makes it difficult to determine the total time between batching and placement in the formwork. Ideally, this should be less than 1.5 hr. With LDC, the shorter the period, the better the quality control will be. Some low-density aggregates may continue to absorb water with time, even though they have been preconditioned with respect to moisture content. Preconditioning slows the rate of absorption but, for some low-density aggregates, may not necessarily eliminate delayed absorption.

For delivery by mixing truck, a common practice by ready-mixed concrete producers is to hold back 10 to 15 L/cu m (2 to 3 gal of water per cubic yard) of concrete to ensure that the concrete is not too wet upon arrival. If that water or some additional water is needed to provide the required workability, it is added to the truck and additional truck mixing is done. This is contrary to the Corps of Engineers standard policy that no water be added to the concrete after it is batched. However, for LDC, this action will not detract from the intended strength since the original proportions were predicated on "free," not "absorbed," water to produce the desired strength at that slump. The unit weight of the concrete will most likely increase when this is done, however, and that may be undesirable if the specifications require a certain weight of the concrete. This problem can be minimized by having the aggregate thoroughly saturated before batching. When water is added, the mixer should be operated at mixing speed for a minimum of 30 revolutions before it is discharged.

If truck mixers are used, they should be operated at prescribed mixing speeds for the range of total revolutions required to produce complete mixing, normally 70 to 100 revolutions. The truck mixer can then be slowed to agitating speed. Prior to unloading any truck, it is desirable that the mixer be rotated at mixing speed for 1 to 2 min. It is also desirable to stop the unloading operation when the drum is about one-half empty and to reverse the drum in the mixing direction for three or four revolutions at mixing speed to ensure continued uniformity of the mixed material being delivered.

4.4.2 Temperature effects

The temperature of the individual ingredients and the resulting temperature of the concrete mixture affect the total water requirements. Mixture temperatures from 10 to 30 °C (50 to 86 °F) generally have no adverse effects on the mixture. Higher temperatures generally increase the mixing water requirements. Moisture preconditioning of the low-density aggregate is essential in reducing the temperature of the concrete and reducing the amount of mixing water absorbed by the aggregate. Premature stiffening or loss of slump may be caused by a high mixture temperature and has nothing to do with a shortage of water in the mixture. Water added under these conditions may produce serious losses in strength and other properties. Whenever possible, efforts should be undertaken to shorten delivery time under hot weather conditions.

5 Conveying and Placing

5.1 General Considerations

Low-density concrete can be transported by the same means used for normal-density concrete. This includes truck mixers, open-top truck bodies with and without agitators, buckets hauled by truck or railroad car, as well as pipeline, hose, or conveyor belts. The method of transportation used should effectively deliver the LDC to the point of placement without significantly altering its desired properties with regard to cementitious ratio, slump, air-content, density, and homogeneity. Each method of transportation has advantages under particular conditions, such as mixture ingredients and proportions, type and accessibility of placement, required delivery capacity, location of the batch plant, and weather conditions. The various conditions should be carefully reviewed in selecting the type of transportation best suited for economically obtaining quality concrete in place. ACI 304R provides descriptions of the various concrete transportation systems. Engineer Manual 1110-2-2000 (HQDA 2001, paragraph 7-5) provides requirements for these types of systems that also apply when used for LDC.

Transportation of LDC by pumping methods and by conveyor belt requires some special attention and is discussed in paragraphs 5.2 and 5.3 of this guide, respectively.

5.2 Pumping

5.2.1 General considerations

Paragraph 10-6 of EM 1110-2-2000 describes the requirements for pumping normal-density structural concrete. For the pumping of LDC, some adjustments to those requirements will be necessary.

The surface texture of low-density aggregates is considerably different from normal-density aggregates (see paragraph 2.3.2 of this guide). The low-density aggregates generally have a surface texture that can vary from angular crushed to round coated. In general, the structural low-density aggregates have the following characteristics in common:

- They are made up of nonconnected voids.
- Bulk saturated specific densities range from 1.10 to 1.60.

- Maximum size aggregate is typically 19 mm (3/4 in.).

5.2.2 Aggregate moisture conditioning

The ability of low-density aggregate to absorb large amounts of water in a 24-hr period is a possible cause for difficulty in pumping. If not highly saturated prior to concrete batching, the low-density aggregates will absorb part of the mixing water both during mixing and when subjected to pump pressures, thus resulting in a significant loss of workability of the concrete and possible variations in the freshly mixed density of the concrete. The total amount of water absorbed by low-density aggregate soaked or sprinkled at atmospheric pressure increases with time. However, for some low-density aggregates, the rate of absorption is initially very rapid but later tapers off.

The moisture preconditioning of the aggregates prior to batching and pumping can be accomplished in a number of ways, as outlined below.

- ***Full immersion.*** This is the most effective way to ensure that the low-density aggregates have the optimum amount of moisture in them prior to batching. However, this method will be the most resisted by the contractor and concrete supplier because it requires some additional facilities and special handling. The project specifications must be specific that full immersion for 24 hr is required, rather than a general provision for "aggregate conditioning." This can also be done at the aggregate plant before shipping and then followed up with atmospheric soaking at concrete plant.

- ***Atmospheric.*** This uses a soaker hose or sprinkler system. A soaking for a minimum of 48 hr should be required, with 5 to 7 days or more preferred. This is dependent on the rate of absorption of the aggregate and effectiveness of the soaking system used, so the aggregate supplier should be consulted. This soaking can initially be done at the aggregate plant where water from spray bars is applied directly onto the aggregates moving on belts and then supplemented at the concrete plant by stockpile hose and sprinkler systems.

- ***Vacuum.*** In this method, the aggregate is placed in a vessel from which the air can be evacuated. The vessel is then filled with water and returned to atmospheric pressure or greater. Typically, this is done at the aggregate plant only.

The additional moisture added to the low-density aggregate in the preconditioning process increases the saturation level of the LDA, which in turn increases the loose density of the low-density aggregate, which ultimately increases the density of the unhardened concrete. Some of this moisture will be lost to the atmosphere in drying. The additional moisture also provides for beneficial internal curing of the concrete, thus improving the long-term mechanical properties of the concrete.

5.2.3 Moisture retention

Having initially preconditioned the low-density aggregates by one of the methods described above, it is essential to maintain the high level of moisture in the aggregate while it is stockpiled. Low-density aggregate preconditioned by the atmospheric method should be used soon after it has reached the desired level of saturation. Aggregates preconditioned by the full immersion or vacuum method generally will retain much higher levels of moisture for longer periods of time. Depending on local conditions, this could be up to 60 days without significant loss of moisture. However, to ensure consistent uniformity, sprinkler systems or soaker hoses should be kept operating on the aggregate stockpiles, regardless of how the aggregate was preconditioned, to ensure there is not significant moisture loss. Sprinkling should be temporarily discontinued when free moisture appears at the base of the material. The moisture content of the pre-preconditioned material should exceed the average 24-hr absorption as measured by ASTM C 127. To achieve uniform slump control, free water should be allowed to drain away before using the aggregate in concrete.

Ideally, a minimum of two stockpiles for each aggregate should be required. One stockpile is made ready and used for production, while the other stockpile is being conditioned. Any preconditioned stockpile that is used will then have had moisture applied to it the previous day(s). This is particularly necessary during peak production periods. The aggregate pile needs to be turned over with an end-loader 2 or 3 times per day to ensure uniform presoaking.

Continued moisture conditioning of the aggregate during the winter season can be a problem if proper planning is not done. Saturating the low-density aggregate makes it prone to the accumulation of ice and frozen lumps of the aggregate. This potential problem has been effectively handled by planning for heating of the stockpiles before the stockpiles are set down. The heating can be done in several ways, the most efficient being a grid of hot water or steam pipes that underlie the stockpiles. The stockpile is then selectively "mined" from the bottom to obtain the unfrozen aggregates. The other surface and near-surface aggregates gain proximity and then thaw as the already thawed aggregates are removed. However, care must be taken not to overheat the LDA, which can cause moisture to be evaporated off and ultimately to result in slump loss.

5.2.4 Pumps and pump systems

The same type of equipment used to pump normal-density concrete can be used to pump LDC. Concrete pumps can be either truck- or trailer-mounted and range from small units—exerting pressures from 1.7 to 2.1 MPa (250 to 300 psi) and outputs of 11 to 23 cu m/hr (15 to 30 cu yd/hr)—to large units that exert pressures of 7 MPa (1,000 psi) and outputs up to 190 cu m/hr (250 cu yd/hr). The effective capacity of the pump depends not only on the pump itself but also on the complete system. Several factors (including line length, number of bends in the line, type of line, size of line, height to which the concrete is being pumped, and the concrete mixture) affect the working capacity of a concrete pump. Significantly higher pressure may be required for vertical pumping and extended

pumplines. Detailed descriptions of the pumps and pump systems can be found in ACI 304.2R.

Some of the key items pertinent to the pump and pumping systems for LDC are as follows:

- Use the largest size line available, preferably a minimum of 125 mm (5 in.).

- All lines should be clean, the same size, and "buttered" with grout at the start.

- Avoid rapid size reduction from the pump to the line. For example, a 250-mm (10-in.)-diam to 100-mm (4-in.)diam transition over 1.2 m (4 ft) will not work as well as a 250-mm (10-in.)-diam to 150-mm (6-in.)-diam transition over 2.4 m (8 ft), or as a 150-mm (6-in.)-diam to 100-mm (4-in.)-diam transition over 1.2 m (4 ft).

- The operating pressures should be as low as practical. This can be helped by slowing down the rate of placement, using as much steel line and as little flexible line as possible, limiting the number of bends and reducers in the line, and ensuring that the lines are tightly joined and gasketed.

5.2.5 Mixture proportions

The mixture proportions established for a job should take into consideration possible slump loss that may occur during both transporting and pumping. Generally, the slump of the LDC going into the pump must be increased and the coarse aggregate content must be reduced, sometimes by as much as one-third of the quantity normally used in a LDC that will not be pumped. When pumping concrete containing low-density aggregates, some adjustments will be necessary to achieve the desired characteristics. The ready-mixed concrete producer and the aggregate supplier should be consulted so that the best possible pump mixture can be determined. Some general rules in proportioning are as follows:

- Precondition the low-density aggregate with respect to moisture by one of the methods described in paragraph 5.2.2 above.

- Maintain a 335-kg/m^3 (564-lb/yd^3) minimum cement content.

- Use selected admixtures that will aid in pumping.

  -- Air entrainment sufficient for 5 to 8 percent air.
  -- Water reducer.
  -- Fly ash or natural pozzolan.
  -- Pumping aid.

- To facilitate pumping, adjustments in the standard mixture proportion usually consist of some slight reduction in the volume of coarse aggregate, with a corresponding increase in the volume of fine aggregate.

- Cementitious content should be sufficient to accommodate a 100- to 150-mm (4- to 6-in.) slump.

- If normal-density sand is to be used in the mixture, ensure that it is well graded, with the fineness modulus (FM) between 2.2 and 2.7. If this FM is not available, consider the addition of a fine sand or mineral admixture.

- Use a properly combined coarse and fine aggregate gradation proportioned by volume that will prevent the paste from being squeezed through the voids between aggregate particles. The gradation comparison should be made by volume rather than by weight to account for differences in specific gravity of various particle sizes.

Tables 5.1 and 5.2 are based on the collective experience of the members of ACI 304 and are a guide for the amount of coarse lightweight aggregate that might be selected for trial mixtures when atmospherically soaked or fully immersed aggregates are used. These values are suggestions only and may easily vary as much as 10 percent above or below those shown for particular local conditions, as well as for specific pumps.

Table 5.1
Suggested Volumes of Atmospherically Soaked Low-Density Aggregate per Cubic Meter of Concrete to Be Pumped

Type of Fine Aggregate	Coarse Lightweight Size Range		
	9.5 to 4.75 mm (3/8 in. to No. 4)	**12.5 to 4.75 mm (1/2 in. to No. 4)**	**19.0 to 4.75 mm (3/4 in. to No. 4)**
Coarse: FM 2.80-3.00	0.293 to 0.322 (7.9 to 8.7)	0.344 to 0.389 (9.3 to 10.5)	0.437 to 0.467 (11.8 to 12.6)
Medium: FM 2.60-2.80	0.307 to 0.337 (8.3 to 9.1)	0.378 to 0.407 (10.2 to 11.0)	0.452 to 0.482 (12.2 to 13.0)
Fine: FM 2.40-2.60	0.322 to 0.344 (8.7 to 9.3)	0.393 to 0.422 (10.6 to 11.4)	0.463 to 0.496 (12.5 to 13.4)

Note: Values shown in this table are in loose cubic meters (cu ft) of atmospherically soaked aggregate per cubic meter (cu yd) of concrete. This may be applied to either crushed or coated particles. Total weight is obtained by multiplying these figures times the unit weight in kilograms per cubic meter (lb/cu ft) for the particular aggregate being used. It is suggested to apply this only to relatively low pump pressures in 100-mm (4-in.) pipelines. The sum of the vertical lift in elevation plus one-third the total length of the distribution line should preferably be less than 45 m (150 ft).

5.2.6 Coarse low-density aggregate

The gradation of coarse lightweight aggregate should fall within the limits stated in ASTM C 330. Many Corps specifications require 19-mm (1-in.) NMSA, but almost all low-density aggregate producers will have only 12.5- or 19.0-mm (1/2 or 3/4 in.) NMSA, or both, available. To specify larger sizes greatly increases the cost of the aggregates and creates other handling and batching problems.

Table 5.2 Suggested Volumes of Fully Immersed Low-Density Aggregate per Cubic Meter of Concrete to Be Pumped			
	Coarse Lightweight Size Range		
Type of Fine Aggregate	9.5 to 4.75 mm (3/8 in. to No. 4)	12.5 to 4.75 mm (1/2 in. to No. 4)	19.0 to 4.75 mm (3/4 in. to No. 4)
Coarse: FM 2.80-3.00	0.393 to 0.426 10.6 to 11.5	0.482 to 0.518 13.0 to 14.0	0.582 to 0.618 15.7 to 16.7
Medium: FM 2.60-2.80	0.411 to 0.448 11.1 to 12.1	0.500 to 0.537 13.5 to 14.5	0.600 to 0.637 16.2 to 17.2
Fine: FM 2.40-2.60	0.430 to 0.467 11.6 to 12.6	0.518 to 0.556 14.0 to 15.0	0.618 to 0.656 16.7 to 17.7

Note: Values shown in this table are in loose cubic meters (cu ft) of fully immersed aggregate per cubic meter (yd$^{3)}$ of concrete. This may be applied to either crushed or coated particles. Total weight is obtained by multiplying these figures times the unit weight in kilograms per cubic meter (lb/cu ft) for the particular aggregate being used.

It is important to note that low-density aggregates may fluctuate in their unit weight. Such variations, within limits, are recognized and permitted by ASTM C 330. These changes in unit weight may be due to the different expanding characteristics of the raw material during processing, changes in moisture content, changes in gradation, or combinations of the three. Adjustments in batch weights to compensate for these changes are imperative to maintain consistent absolute volumes of aggregate and proper yield.

Structural low-density aggregates may have a coated or uncoated exterior surface, depending on the production method. As described in paragraph 2.3.2, they may also be rounded, cubical, or angular-shaped pieces. In any case, proper allowances should be made for shape and surface texture to handle any type of low-density aggregate in a pump mixture. These allowances are made by slight changes in the ratio of mortar to coarse aggregate.

Often, low-density aggregates larger than 4.75-mm (No. 4) screen are produced in two separate fractions. These two sizes should be combined (preferably at the batch plant) to produce a blended total coarse aggregate combination that satisfies ASTM C 330. Uniformity of gradation should be carefully maintained from one batch to the next, since fluctuations will affect the degree of pumpability.

5.2.7 Fine low-density aggregate

Gradation. The gradation of fine low-density aggregate should also fall within the limits of ASTM C 330. In addition, it is imperative to pay specific attention to the very fine fractions, as these are often deficient in fine low-density aggregate. Between 20 and 35 percent should pass the 300-μ (No. 50) screen and 10 to 20 percent should pass the 150-μ (No. 100 screen). If the low-density fine aggregate is deficient in these sizes, some aggregate supplement or mineral admixture, such as pozzolan, fly ash, or rock dust in approximately the amount of the deficiency, will improve pumpability.

When combining low-density fine aggregate with natural sands, it should be noted that, while the overall gradation of the combined fine particles may be improved, the combination will increase the weight of the finished concrete mixture. Adverse weight effects can be minimized by using relatively small amounts of very fine natural sands if this combination results in improved gradation. Although the pumpability of a mixture may be enhanced by the addition of minus-50 to minus-200 mesh fractions in the fine aggregate, it must be kept in mind that too great of an increase in these very sizes will require greater amounts of mixing water that, in turn, may reduce the concrete strength and increase the drying shrinkage.

Fineness modulus. The FM of low-density fine aggregate requires some additional understanding and is described in ACI 211.2 and in paragraph 3.3.3 of this guide.

Pumpable mixtures containing all normal-density aggregates typically pump the best when the FM of the fine aggregate is between 2.40 and 3.00. For a LDC mixture, that range should then be 2.20 to 2.80 after the reduction of 0.20. Experience to date does not indicate the need for any greater accuracy. If natural sand is blended with the low-density fines, the combined FM calculated on a weight basis should also fall within the limits of 2.20 to 2.80.

5.2.8 Water and slump

For LDC, the total water requirements will be different than for normal-density mixtures. This is due to the absorptive properties of the aggregate. If the total water in a LDC mixture is divided into two segments, that is, into "free" water and "absorbed" water, it simplifies the considerations. The free water will establish the slump and have a direct bearing on the water-cementitious material relationship. The absorbed water, however will be contained within the lightweight particles and will not change their displaced volume in the mixture. Also, the absorbed water will not directly affect the quality of the paste. The requirements for free water in LDC are approximately the same as for a similar mixture of normal-density concrete. The absorbed water will vary, however, and to minimize these variations, the moisture preconditioning of the low-density aggregate is a necessity.

Experience indicates that slumps from 50 to 150 mm (2 to 6 in.) are most suitable for pumping. In mixtures with higher slumps, the aggregate will separate from the mortar and paste, and possibly cause pumpline blockage. Overly wet mixtures also exhibit excessive bleeding, loss of entrained air, and increased shrinkage. However, slumps above 150 mm (6 in.) obtained through the use of superplasticizers are usually pumped without difficulty.

If additional absorption in LDC does occur during truck mixing and transportation, the mixture should be brought to the specified slump before pumping by the addition of extra water to offset that which was observed (see paragraph 4.4.1). As noted earlier, this action will not detract from the intended strength of the LDC, since the original proportions were predicated on free, not absorbed, water to produce the desired strength at that slump.

If a slump loss takes place in low-density mixtures between the pump and the end of the discharge hose, this may be due to further aggregate absorption under pressure caused by insufficient saturation of the low-density aggregate, too much coarse aggregate for a pumpable mixture, high pumping pressures, or a combination of these. If the slump at the end of the discharge hose can be maintained within specification limitations, it may be satisfactory for the concrete to enter the pump at a higher slump to compensate for slump loss if, as previously stated, the change is simply due to aggregate absorption.

5.2.9 Cementitious materials

General. The cementitious materials contents for pumpable LDC follow the general principles discussed in ACI 211.2 for LDC. It is recommended that the low-density aggregate producer be consulted on cementitious materials content requirements for his particular material to meet the necessary strengths. It should be recognized that pumpable low-density mixtures that use higher ratios of fine to coarse aggregate or higher slump may require an upward adjustment in cement contents.

In establishing the cement content for pumpable low-density trial mixtures, it should be remembered that there is a need for overstrength proportioning in the laboratory to provide for field variations (see ACI 318, paragraph 5.3).

The use of extra quantities of cementitious material as the only solution to correct pumping difficulties is shortsighted and uneconomical. It is far more desirable to correct any deficiencies in the aggregate gradation, especially in the fine aggregate fraction, and to correct the initial moisture content of the low-density aggregate.

Mineral admixtures. Finely divided mineral admixtures used in pumpable mixtures may be classified into three types:

- Relatively chemically inert material such as ground limestone, ground quartz, and hydrated lime.

- Cementitious materials such as natural cement, ground granulated blast furnace slag (ASTM C 989), hydraulic lime, and slag cements (ASTM C 595).

- Pozzolans such as Class C and F fly ash, diatomaceous earth, volcanic glass, some heat-treated shale or clays (all the preceding are covered in ASTM C 618), metakaolin, rice hull ash, and silica fume (ASTM C 1240).

Many of these materials have particle sizes as small or smaller than portland cement. Some have a beneficial strength effect on the concrete mixture and can be used to enhance pumpability due to their spherical particle shape and smooth, dense surface texture.

In aggregate gradations deficient in fines, as are most low-density aggregates, the addition of a finely divided mineral admixture generally improves workability and pumpability, reduces the rate and amount of bleeding, and increases strength. The effect on strength depends on the type of mineral admixture used, conditions under which the concrete is cured, and the amount of admixture used.

5.2.10 Admixtures

Any admixture that increases workability of LDC will usually improve pumpability. The choice of admixture and the advantage gained from its use in concrete to be pumped will depend on the characteristics of the pump mixture. When the admixture is used as an aid in pumping, it may provide additional lubrication, reduce segregation, and decrease bleeding.

Admixtures used to improve pumpability are generally classified as

- Water-reducing and high-range water-reducing (superplasticizer) admixtures (ASTM C 494).
- Air-entraining admixtures (ASTM C 260).
- Finely divided mineral admixtures as described above.

Refer to ACI 212.3R for a general discussion of all types being used.

High-range water-reducing admixtures (HRWRA), sometimes referred to as superplasticizers, are often used when pumping LDC. However, it should be noted that they are effective only for a limited time. Low-density concrete that depends on HRWRA for pumpability must be discharged from the pumpline before any reduction in slump occurs. It is recommended that these admixtures be included in the trial mixture program if their use is proposed. The concrete should have a 75-mm (3-in.) slump before the HRWRA is added. Compatibility of the mixture ingredients should be closely watched, as rapid and significant loss of air content has been experienced with some HRWRA. HRWRA can be added at the placement site, if necessary, to stay within the working life of the admixture. In some instances, HRWRA have shown a tendency to adversely affect finishing operations. Varying degrees of stiffness, attributed to the HRWRA, at the surface of fresh concrete can make the surface more prone to tears and separation.

Any LDC that will be pumped should have air entrainment. With air entrainment, the LDC will be considerably more cohesive and workable than a non-air-entrained concrete. The LDC can be pumped with less coarse aggregate segregation and there is less tendency for the concrete to bleed. Start-up and shutdown with the pipeline full is generally easier with air-entrained concrete than with non-air-entrained concrete due to reduced bleeding. Bleeding sometimes results in loss of lubrication, which tends to cause pipeline blockage.

In all cases, air entrainment is required if the concrete is to be exposed to freezing and thawing cycles.

The amount of air entrainment in LDC should be between 5 and 8 percent. It is not unusual for the concrete to lose 1.0 to 1.5 percent of the air as a result of the pumping action and vertical dropping of the concrete from the end of the pumpline. When specifications call for a certain air-content range at the discharge point from the pump hose, the air content should be increased during batching to compensate for the loss, if any, during handling and placing using a pump system.

In general, the influence of pumping on air-entrained LDC can be minimized by maintaining the lowest possible pump pressures, by minimizing "free fall" within a vertically descending pipeline, and by reducing impact by directing the discharge from the hose into previously placed concrete.

5.2.11 Pumpability tests

No standard laboratory test method is available to accurately evaluate the pumpability of a LDC mixture. In general, mixtures with low-density fines and mixtures with unit weights considerably less than 1,842 kg/m^3 (115 lb/ft^3) are more difficult to pump. However, a field trial should be conducted using the pump and mixture design intended for use on the project. Observers present at this trial should include representatives of the contractor, ready-mixed concrete producer, architect and engineer, pumping service, testing agency, and aggregate supplier.

The pumping test should include a sizable quantity of the mixture and pumping of it under conditions involving the pressures and placing rates anticipated for the work to be done. Often, this field trial is performed at the construction site as a part of the more routine initial or demonstration placements. In the pump trial, the height and length the concrete is to be moved should be taken into account. Since most test locations will not allow the concrete to be pumped vertically as high as it would be during the project, the following rules-of-thumb can be applied for the horizontal run with steel line:

- 0.30 m (1.0 ft) vertical = 1.22 m (4.0 ft) horizontal
- 0.30 m (1.0 ft) flexible line = 0.61 m (2.0 ft) of steel line
- 0.30 m (1.0 ft) 90-deg bend = 0.91 m (3.0 ft) of steel line

Prior use of a mixture and pumping equipment on another job may furnish evidence of pumpability if job conditions are duplicated.

5.2.12 Field control

Pumped LDC does not require any compromise in quality. However, it does require a high level of quality control to ensure that concrete uniformity is maintained. Changes in absorbed moisture or density of low-density aggregates (which result from variations in initial moisture content, gradation, or specific

density) and variations in entrained-air content require frequent checks (see ACI 211.1).

The locations at which samples for testing the concrete are taken are extremely important. Sampling, according to ASTM C 94, is for the acceptability of the ready-mixed concrete. However, water absorbed by the aggregates during pumping can increase the unit weight of the concrete by as much as 32 kg/m^3 (2 lb/ft^3). Tests run at the pump hopper may indicate a unit weight of 1,842 kg/m^3 (115 lb/ft^3) while tests at the end of the pumpline may produce a unit weight of 1,874 kg/m^3 (117 lb/ft^3). To avoid disputes about compliance with the specifications, the concrete producer needs to know that the quality of the concrete being placed in the structure will be measured at the placement end of the pumpline.

Where appropriate, sampling at both the truck discharge and point of final placement should be employed to determine if any changes in the slump, air content, and other significant mixture characteristics have occurred as a result of the pumping. When sampling at the end of the placement line, great care must be taken to ensure that the sample taken is representative of the concrete going into the placement. Changing the rate of placing and/or the boom configuration can result in erroneous test results. Concrete must not be allowed to freefall into the tester's container. The handling of the sample must not result in changes in the concrete properties.

Four simple tests are normally required:

- Standard slump test (ASTM C 143).
- Unit weight of the fresh concrete (ASTM C 567).
- Entrained air content (ASTM C 173).
- Compressive strength (ASTM C 39).

At the job start, the unhardened properties, unit weight, air content, and slump of the first several batches should be determined to verify that the field concrete conforms to the laboratory mixture. Small adjustments may then be made as necessary. In general, when variations in the fresh unit weight exceed ±2 percent, an adjustment in batch weights will be required to meet specifications. The air content of LDC should not vary more than ±1.5 percentage points from the specified value to avoid adverse effects on hardened density, compressive strength, workability, and durability.

It takes a considerable amount of time to perform the volumetric air test (ASTM C 173), and it may not be practical to perform that test on every batch produced without delaying the pumping delivery of the concrete. Initially, at the start of the project, every batch should have its air content measured until sufficient data are produced to make a correlation between the unit weight and the air content of the concrete. If a good correlation exists, the frequency of the

air content measurements can then be relaxed to once every 20 or 40 cu m (25 or 50 cu yd) with the unit weight still being measured for every batch. At a minimum, in accordance with ASTM C 31, the air content should be tested each time strength specimens are made. When the concrete is being placed by pump, it is recommended that the concrete be sampled for acceptance testing at the point of discharge of the pump. While it is recognized that there can be disagreement over the proper sampling point with pumped concrete, given the magnitude of the effects pumping can have on LDC, the author believes this recommendation is warranted in the case of LDC.

Low-density concrete has been successfully pumped during both hot and cold weather. Precautions may be necessary to provide protection during extreme conditions. The placing crew and inspector should always be alert to any segregation of the concrete as it is discharged from the pipeline. If segregation occurs, it may be necessary to modify or change the placing practice to eliminate or minimize the segregation.

5.2.13 Planning

Proper planning of the entire pumping operation, including pump location, line layout, placing sequence, and concrete supply, will result in savings of time and expense. The pump should be as near the placement as possible. Concrete delivery systems should have easy access to the pump. Lines from the pump to the placement area should be made up primarily of rigid pipe and contain a minimum number of bends. For large placement areas, alternate lines should be laid for rapid connection when required, and standby power and pumping equipment should be readily available (onsite) to replace an initial piece of equipment should a breakdown occur.

5.2.14 Other requirements

When pumping downward 15 m (50 ft) or more, an air release valve at the middle of the top bend will prevent vacuum or air buildup. When pumping upward, a shutoff valve near the pump will prevent reverse flow of concrete during the fitting of cleanup equipment or when working on the pump. Direct communication should be maintained between the placing crew and the pump operator. Good communication between the pump operator and the concrete batch plant is also important. It is desirable to have the concrete delivery such that the pumping can proceed continuously.

When a delay occurs, it may be difficult to start the concrete moving in the line again, especially if the delay has been for a considerable length of time. This critical delay time will depend upon such factors as the concrete mixture, temperature, length of pipeline, and type of pump. It may be necessary to clean the line and start again if the delay becomes extended. A grout or mortar should be used to lubricate the pipeline anytime pumping is started with clean lines, but it should not be pumped into the forms.

5.3 Conveyor Belts

Low-density concrete has been successfully placed using conveyor belts. The best success has been when the slumps were between 2 and 4 in. (51 and 102 mm) with a homogeneous concrete mixture. Belt speed becomes more critical when the slump is outside this range. Slow conveyor belts are generally unacceptable because they produce segregation in the concrete. Engineer Manual 1110-2-2000 notes that any belt traveling less than 300 ft (91 m)/min is considered slow. Detailed information on the parameters and specifications for belt placement of normal-density concrete is contained in ACI 304.4R and is also applicable to LDC. The use of any belt conveyor should be discontinued if excessive segregation occurs.

5.4 Placing

Placement of LDC can be accomplished with buckets, hoppers, manual or propelled buggies, chutes and drop pipes, conveyor belts, pumps, tremies, and paving equipment. Historically, most concrete for Corps civil works projects has been placed using cranes and buckets. These are quite acceptable for use with LDC. Recently, however, the preferred placing equipment for mass and structural concrete has been conveyors and pumps, respectively. Both of these are also acceptable for placing LDC and are discussed in paragraphs 5.2 and 5.3. Mixture proportions, conveying methods, and placing restrictions must be considered for each portion of the project during preconstruction engineering and design to ensure that the appropriate concrete is placed in each feature.

The basic requirement in placing LDC is that both quality and uniformity of the concrete (in terms of w/c or w/(cm), slump, air content, and homogeneity) are preserved. The selection of the handling and placing equipment should be based on its capability to effectively handle LDC of the most advantageous proportions that can be consolidated in place with vibration. Equipment that requires adjustment in mixture proportions beyond the ranges recommended in ACI 211.2 and this guide should not be used.

The LDC should be deposited in approximately its final position in the structure where it is to remain and should not be moved within the forms or mass using vibrators. It is more prone to segregation than normal-density concrete when attempts are made to move it around using vibration. As a general rule, the LDC should not be allowed to fall more than 1.5 m (5 ft) from the end of its discharge device (hose, bucket, belt, buggy, etc.). With buckets, elephant trunks with a rigid drop-chute bottom section should be used. All belt conveyors must have elephant trunks at their discharge end.

The thickness of layers for LDC are typically 20 percent less than for normal-density concrete. Layers should be limited to a maximum of 400 mm (16 in.).

Because of the large amounts of water (both free and absorbed) that may be included in LDC, no concrete placement should begin if there is a remote

possibility that the concrete will freeze before it has developed adequate strength to resist the freezing. Adequate facilities for cold weather protection can be provided (see ACI 306R).

It is advisable that the LDC be delivered to the site at a uniform rate compatible with the manpower and equipment being used in the placing and finishing processes. With LDC, interruptions in the concreting process are more problematical than with normal-density concrete because of the possibility of continual moisture absorption from the mixture by the aggregates. Consideration should be given to having backup equipment for large placements.

Other typical placing considerations for normal-density concrete described in ACI 304R and EM 1110-2-2000 also apply to LDC.

5.5 Consolidation

5.5.1 Vibration behavior

During vibration of LDC, the entrapped air bubbles are brought to the surface through buoyancy and are dissipated as for normal-density concrete. However, the lower density of the mixture results in somewhat less buoyancy for the air bubbles. It is important to allow enough vibrating time to remove the air bubbles, while noting that with lengthy vibration times much of the entrained air may be lost and some of the low-density particles may float.

Segregation of the concrete mixture ingredients during vibration is caused by differences in their specific densities. In normal-density concrete, the coarse aggregate is heavier than the mortar and therefore tends to sink during vibration. In LDC, the reverse is true, although the tendency for the coarse aggregate to float is less when the mortar contains low-density fine aggregate. Dry mixtures will not segregate as rapidly under vibratory action as wet mixtures.

5.5.2 Consolidation equipment and procedures

Corps of Engineers guidance on the consolidation of normal-density concrete is found in EM 1110-2-2000, paragraph 8-2f. A thorough discussion of consolidation is given in ACI 309R. The equipment and procedures recommended for consolidating normal-density concrete are also suitable for LDC, with some additional considerations as described in the following paragraphs.

As for normal-density concrete, LDC should be placed as closely to its final position as practicable to avoid segregation. Vibrators should not be used to move the concrete laterally. Shovels are frequently helpful in depositing or moving the concrete.

Low-density concrete should be deposited in layers compatible with the work being done. In large mats and pedestals, the maximum layer depth should be limited to 400 mm (16 in.). The depth will typically be less than the vibrator head

length. In walls and columns, the layer depths should not exceed 400 mm (16 in.). It should be noted that these layer depths are typically about 80 percent of those used for normal-density concrete.

After the surface of the LDC is leveled, the vibrator should be inserted vertically at a uniform spacing over the entire placement area. The distance between insertions should not be greater than 1.5 times the radius of action and should be such that the area visibly affected by the vibrator overlaps the adjacent just-vibrated area. The vibrator should penetrate the previous layer. Sufficient time, usually about 10 sec, should be given each insertion to obtain adequate consolidation. Stiffer mixtures may require a few additional seconds.

5.5.3 Walls

Revibration of the tops of walls normally results in a more uniform appearance of vertical surfaces. On LDC walls, where surface voids are objectionable, the following procedure has been successfully used. Each layer should be vibrated in the normal manner, and then immediately revibrated prior to placing the succeeding lift. If a period of about 30 min (or as long as practical) is allowed between vibration operations, this procedure can be quite effective. As an alternative to the second vibration, which may require additional vibrators, hand-spading or spudding against the form surface has been moderately effective.

5.5.4 Floors

In the construction of concrete floors, the recommendations of ACI 309R should be followed with some additional precautions when using LDC.

Air entrainment and minimal slump are both very desirable. These will assist in preventing the low-density aggregate particles from coming to the surface.

Best consolidation is obtained by dragging the vibrator through the concrete in a nearly horizontal position at about the same spacing as used for vertical insertions. Dragging at a constant velocity will give more uniform vibration than jerking motions. In lieu of internal vibrators, vibrating screeds may be used for thin floors where there are no obstructions to impede their use.

When segregation has occurred, a hand-operated grid tamper or mesh roller may be used to depress the floating low-density coarse aggregate slightly below the top surface.

6 Other Construction Considerations

6.1 Forms

The U.S. Army Corps of Engineers Unified Facilities Guide Specification UFGS-03101, "Formwork for Concrete," should be included in any specification for a project that includes low-density concrete. There are no special requirements for formwork when it is used for LDC. The lateral pressure, p, on the formwork, where $p = wh$ (where w = unit weight of the fresh concrete, and h = depth of the unhardened concrete) can be reduced in formwork design because of the lower density of the concrete. Detailed information on formwork can be found in ACI 347R.

6.2 Finishing

The finishing requirements given for normal-density concrete in paragraph 8-3 of EM 1110-2-2000 (HQDA 2001) also apply to LDC. However, the finishing procedures for LDC differ somewhat from those used for a normal-density concrete. Because the density of the low-density coarse aggregate is generally less than that of the sand and cement, working the concrete has a tendency to bring the coarse aggregate, rather than the mortar, to the surface. This should be taken into account in the finishing operations. ACI 302.1R has provided several simple rules to control this tendency so that LDC can be finished as easily as normal-density concrete, provided the mixture has been properly proportioned. These rules (given below) assume the use of low-density coarse aggregate and normal-density fine aggregate.

- The mixture should not be over-sanded in an effort to bring more mortar to the surface for finishing. This usually will aggravate rather than alleviate finishing difficulties.

- The mixture should not be under-sanded in an attempt to meet the unit weight requirements. Neither mixing to the recommended slump nor entrainment of air will effectively control segregation in such a mixture.

- The LDC mixture should be proportioned to provide proper workability, pumpability, finishing characteristics, and required setting time, to minimize

segregation or the tendency for coarse aggregate particles to rise above the heavier mortar.

- Some low-density aggregates can require further control of segregation, or bleeding, or both. For this purpose, air entrainment at levels not less than 4 percent is useful.

- The preconditioning of the low-density aggregates (as described in paragraph 5.2.2 of this guide) is a necessity for concrete that will be pumped.

- Overworking or overvibrating LDC should be avoided. A well-proportioned LDC mixture can generally be placed, screeded, and bull floated with approximately one-half the effort considered good practice for normal-density aggregate. Excess darbying or bull floating are often principal causes of finishing problems, since they serve to drive down the heavier mortar that is required for finishing, and to bring an excess of coarse aggregate to the surface.

- A magnesium darby or bull float should be used in preference to wood. Metal will slide over the coarse aggregate and force it down in the concrete instead of tearing or dislodging it.

- The surface should be floated and flat-troweled as soon as surface moisture has disappeared and while the concrete is still plastic. When cementitious materials are used as part of the binder in the concrete, there may not be much evidence of surface moisture. If floating is done by hand, a magnesium float should be used. With thoroughly preconditioned aggregates with respect to moisture, the evaporation of the surface moisture may not take place soon enough while the concrete is still in a plastic state. The water and excess moisture should then be removed from the surface with as little disturbance as possible. A simple but reliable method is to drag a loop of heavy-rubber garden hose or burlap over the surface.

A complete description of finishing equipment and procedures can be found in ACI 302.1R.

6.3 Curing

The requirements for curing LDC are no different than for normal-density concrete. Curing of LDC has been done successfully using moist curing, curing membranes, and sheet curing. The requirements of paragraph 8-4 of EM 1110-2-2000 and the guidance in ACI 308 should be followed. The free moisture contained in the low-density aggregates provides some autogenous curing with the passage of time.

6.4 Surface Roughening

Extra care must be exercised when green-cutting LDC in preparation for placing fresh concrete against it. The soft, friable nature of the low-density coarse aggregate causes it to be easily eroded away by the high-pressure water jets typically used for surface roughening. The resulting surface typically does not provide sufficient roughness to produce the aggregate interlock that is usually expected by this action. A better solution for horizontal surfaces is the use of commercially available surface retarders that indefinitely inhibit the hardening of the mortar at the concrete surface. The retarder and the mortar it affects are easily washed away by garden-hose spraying without damage to the aggregate, thus leaving adequate exposure of the coarse aggregate. The effectiveness of these retarders should be verified in the laboratory prior to their use to ensure that there is no adverse effect on the bonding of the two placements of concrete. For vertical surfaces, the use of mechanical tiebacks such as hooked bars or studs is recommended to offset the lack of adequate aggregate interlock after green-cutting.

6.5 Job Controls

The control tests discussed here pertain primarily to LDC after mixing has been completed. Other tests can be made on the individual ingredients, particularly the low-density aggregates, in accordance with ASTM C 330.

6.5.1 Sample locations

Samples of LDC for field or jobsite tests should always be taken at two or more regularly spaced intervals during discharge of the middle portion of the load, following ASTM C 172. Samples should not be obtained until after all of the water has been added to the mixer, and should not be obtained from the first or last portion of the load. For pumped concrete, sampling at both the truck discharge and point of final placement should be employed, where appropriate, to determine if any changes in the slump, air content, and other significant mixture characteristics have occurred as a result of the pumping. All testing methods should be performed in accordance with current ASTM test methods.

6.5.2 Slump

The slump test for LDC is performed exactly the same as for normal-density concrete and is in accordance with ASTM C 143. The slump of LDC should be approximately two-thirds that of normal-density concrete to produce equal workability. This is because the low-density aggregates weigh less, and this reduces the effect of gravity.

The slump of the concrete is controlled by the free water in the mixture and is independent of the absorbed water in the aggregate. If the specified slump is obtained at the time and point of placement, it can be assumed that the strength and other properties of the mixture, as originally designed, will have been maintained. Within these stated mixture temperatures, additional water may be

added on arrival at the jobsite only if needed to produce the specified slump as delivered in accordance with ASTM C 94. When the concrete is transported some distance from the truck, particularly if pump placement is used, it is advisable to have comparative slump tests made at the point of placement. In this case, such samples should be remixed in accordance with ASTM C 172 before conducting the slump tests.

6.5.3 Unit weight

The unit weight of the unhardened concrete is important in the control of LDC mixtures and in verifying compliance with structural design criteria. In most cases, the job specifications place an upper limit on the air-dry unit weight in accordance with ACI 301 and with ASTM C 567. Since the air-dry weight cannot be measured at the time of placement, the unhardened unit weight should be used as a field control.

In determining the acceptability of fresh mixtures of LDC, the unit weight should be measured in accordance with ASTM C 138, using a 0.14-cu m (0.5-cu ft) calibrated container. For alternate determinations, such as uniformity, other suitably sized and calibrated containers, including air meter bases or cylinder molds, may be used. If the unit weight measured in the field cannot be maintained within ±32 kg/cu m (±2 lb/cu ft) of the established limits, the yield should be checked as described in ACI 304.5.

In addition to the unit weight of the unhardened concrete, it is also advisable to monitor the unit weight of the oven-dry low-density aggregates at the batch plant. ASTM C 330 provides that these aggregates should not differ more than 10 percent from the weight used in the mixture proportions. A change in the dry unit weight of the low-density aggregates of 10 percent on the coarse fraction would typically produce a variation of 32 to 48 kg/cu m (2 to 3 lb/cu ft) in the unhardened unit weight of the concrete. This amount of variation may not be acceptable for LDC float-in structures, and tighter controls may be necessary.

If the LDC is to be pumped (see paragraph 5.2), the moisture content and absorbed water content of the aggregate should be checked to make certain that sufficient saturation has been achieved to avoid excessive absorption as a result of pumping pressure applied to the concrete.

6.5.4 Air content

Entrained air is typically used in LDC, and its control on the job is essential to obtain quality concrete. In addition to improving some of the durability characteristics of the concrete, air entrainment helps to reduce the weight of the concrete, produces a more cohesive mixture that in turn improves workability, and minimizes the segregation of the heavier mortar from the lighter aggregate particles.

ASTM C 173 is the recommended procedure (volumetric air content) to determine air content of LDC. ASTM C 231 (pressure air content) will measure some of the air within the pores of the low-density aggregate in addition to the air

in the mortar, and therefore is not appropriate for use with LDC. The usually accepted tolerances for air content, including those included in Corps specifications, also apply to LDC. However, variations in the air content also produce variations in the unhardened unit weight. Air contents excessively above those specified can produce substantial reductions in strength (up to 10 percent for every 1 percent air), particularly in the richer (binder contents more than 475 kg/cu m (800 lb/cu yd)) high-strength mixtures. In lean mixtures (binder contents less than 297 kg/cu m (500 lb/cu yd)), there will be only a small strength reduction. A 1-percent increase in air content will typically cause a reduction in unit weight of 16 kg/cu m (1 lb/cu ft). Therefore, it is imperative to maintain tight controls on air content.

Due to the length of time required to complete a volumetric air test, it can be difficult for a QC technician to perform extra air tests beyond those mandated by the project specifications for the regular sequence of testing. However, given the critical nature of having proper control of the air content in LDC, an alternate procedure can be used for intermediate checks on the air content, if so desired. The ASTM C 138 procedure for unit weight, yield, and gravimetric air content can be used for intermediate tests. While the gravimetric measure of air content is generally accepted to be a less accurate measure than the volumetric method, it can be used for intermediate checks on air content that will not be considered as a part of acceptance testing. Similarly, a correlation could be developed between unit weight measurements and the volumetric air measurements, and intermediate unit weight tests then used to estimate air content.

6.5.5 Yield adjustments

Field control of the yield of LDC is most important. Overyield produces a larger volume of concrete than intended, while underyield produces less. Overyield is nearly always associated with a loss of strength, due to a reduction in the net cement content, and also with a reduced unit weight. Underyield results in less concrete being delivered than was expected or ordered, and typically results in an increase in unit weight of the concrete.

The unit weight of the unhardened concrete is used to measure the yield of the mixture. The weight of all the ingredients that are placed in a mixer drum as given on the delivery ticket is added, or the entire truck may be weighed before and after discharging. The total weight includes all the binder materials, the aggregates whether wet or dry, and all of the water added. The unhardened unit weight divided into the weight of all the ingredients will give the total volume of concrete in the mixer drum (ASTM C 138). When the calculated volume is more than 2 percent above or below the volume shown on the delivery ticket, an adjustment is required.

If the change in yield is due to entrained air content, then an adjustment in the amount of air-entraining admixture may correct this condition. When there have been no appreciable changes in the weights of the original low-density aggregates themselves, the differences in yield may be the result of an incorrect amount or an incorrect absolute volume of the low-density aggregate. In this

case, the absolute volume of the low-density aggregates should be corrected at the batch plant as the concrete is being batched.

6.5.6 Test specimens

The test specimens made for LDC are the same as those made for normal-density concrete and should carefully follow ASTM C 31.

6.6 Concrete Quality Verification and Testing

As with normal-density concrete, the contractor will mold, cure, and perform the appropriate tests of LDC as a part of the quality control program. The Government will perform the appropriate testing as a part of its quality assurance plan. The requirements for the contractor's quality control and for the Government's quality assurance plan, as detailed in Chapter 9 of EM 1110-2-2000, also apply to LDC.

References

American Concrete Institute. *Manual of Concrete Practice.* Farmington Hills, MI.

ACI 116R	Cement and concrete terminology.
ACI 201	Conducting condition surveys.
ACI 201.2R	Durable concrete.
ACI 211.1	Selecting proportions for normal, heavyweight, and mass concrete.
ACI 211.2	Selecting proportions for structural lightweight concrete.
ACI 212.3R	Chemical admixtures for concrete.
ACI 214	Evaluation of strength test results of concrete.
ACI 301	Structural concrete for buildings.
ACI 302	Construction of concrete floors.
ACI 302.1R	Concrete floor and slab construction.
ACI 304R	Measuring, mixing, transporting, and placing concrete.
ACI 304.2R	Placing concrete by pumping methods.
ACI 304.4R	Placing concrete with belt conveyors.
ACI 304.5R	Batching, mixing, and job control of lightweight concrete.
ACI 306R	Cold weather concreting.
ACI 308	Curing concrete.
ACI 309R	Consolidation of concrete.
ACI 318	Building code requirements for structural concrete.
ACI 345R	Concrete highway bridge deck construction.
ACI 347R	Formwork for concrete.

American Society for Testing and Materials. *Annual Book of ASTM Standards.* West Conshohocken, PA.

ASTM C 29	Unit weight and voids aggregate.
ASTM C 39	Compressive strength of cylindrical concrete specimens.
ASTM C 31	Making and curing concrete test specimens in the field.
ASTM C 33	Concrete aggregates.
ASTM C 94	Ready-mixed concrete.
ASTM C 127	Specific gravity and absorption of coarse aggregate.
ASTM C 128	Specific gravity and absorption of fine aggregate.
ASTM C 138	Unit weight, yield, and air content (gravimetric) of concrete.
ASTM C 143	Slump of portland cement concrete.
ASTM C 150	Portland cement.

ASTM C 172	Sampling freshly mixed concrete.
ASTM C 173	Air content of freshly mixed concrete by the volumetric method.
ASTM C 192	Making and curing concrete test specimens in the laboratory.
ASTM C 231	Air content of freshly mixed concrete by the pressure method.
ASTM C 260	Air-entraining admixtures for concrete.
ASTM C 330	Lightweight aggregates for structural concrete.
ASTM C 332	Lightweight aggregates for insulating concrete.
ASTM C 494	Chemical admixtures for concrete.
ASTM C 567	Unit weight of structural lightweight concrete.
ASTM C 595	Blended hydraulic cements.
ASTM C 618	Coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete.
ASTM C 845	Expansive hydraulic cement.
ASTM C 989	Ground granulated blast-furnace slag for use in concrete and mortars.
ASTM C 1240	Silica fume for use in hydraulic-cement concrete and mortar.

Expanded Shale, Clay and Slate Institute. Salt Lake City, UT. *http://www.escsi.org.*

Headquarters, Department of the Army. (1999). "Engineering and design for Civil Works projects," Engineer Regulation 1110-2-1150, Washington, DC.

______. (2001). "Standard practice for concrete for civil works structures," Engineer Manual 1110-2-2000, Washington, DC.

Hoff, G. C. (1989). "Evaluation of ice abrasion of high-strength lightweight concretes for arctic applications." *Proceedings, 8th international offshore mechanics and arctic engineering (OMAE) conference*. The Hague, The Netherlands. 3, 583-90.

Holm, T. A., and Bremner, T. W. (2000). "State-of-the-art report on high-strength, high-durability structural low-density concrete for applications in severe marine environments." ERDC/SL TR-00-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://libweb.wes.army.mil/uhtbin/hyperion/SL-TR-00-3.pdf.*

U.S. Army Corps of Engineers. "Unified Facilities Guide Specifications," Washington, DC.

UFGS-03100, Structural concrete formwork.
UFGS-03101, Formwork for concrete.
UFGS-03301, Cast-in-place structural concrete.
UFGS-03307, Concrete (for minor structures).
UFGS-03415, Precast-prestressed concrete.
UFGS-03700, Mass concrete.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2002

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Guide for the Use of Low-Density Concrete in Civil Works Projects

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

George C. Hoff

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WU 33151

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Hoff Consulting, 250 Saddlewood Drive,
Clinton, MS 39056-4070

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/GSL TR-02-13

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Corps of Engineers, Washington, DC 20314-1000;
U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

Technical Report INP-02-7

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This guide provides information for investigating, selecting, and using materials in the production of low-density concrete for civil works concrete structures. As there are many similarities between normal-density concrete and low-density concrete, the elements discussed focus only on those areas in which there are differences between the two—in material types, materials processing, mixture proportioning, batching, placing, consolidation, job controls, and other construction-related issues. Emphasis is placed on use of low-density concrete in hydraulic structures.

Information on plans and specifications, coordination between design and field activities, preparation for construction, concrete quality verification and testing, and reporting are similar for both normal- and low-density concrete and are described in Engineer Manual 1110-2-2000, "Standard practice for concrete for civil works structures."

15. SUBJECT TERMS

Concrete
Low-density aggregate
Low-density concrete
Pozzolans
Specified-density concrete
Structural concrete

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		68	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18